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Appendix A

Supporting Calculations

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Appendix A, GAC Supporting Calculations

Contents

I. Data. The data below are used in the Estimates

Displacement rate during fill from the V-Tanks to the consolidation tanks:

$$F_d := 50 \frac{gal}{min} \qquad\qquad Q_d := F_d \qquad\qquad Q_d = 6.68 \frac{ft^3}{min}$$

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Pressures and Temperatures

$$P := \frac{12.5}{14.7} atm \qquad\qquad T_g := 298K$$

Gas Constants

$$R_g := 0.082 \frac{L \cdot atm}{mol \cdot K} \qquad R_{star} := \frac{R_g \cdot 273.16K}{1 atm} \qquad R_{star} = 22.399 \frac{L}{mol}$$

$$R_{g2} := 1.987 \frac{cal}{mol \cdot K} \qquad\qquad lbmol := 454 mol$$

Volumes/Masses/Densities

$$V_{tks} := 12000 gal \qquad\qquad$$ This is the V-Tank total volume (sludge + liquid)

$$V_{gas} := 2 \cdot 8000 gal - V_{tks} \qquad V_{gas} = 4000 gal \qquad$$ This is the volume of gas in the space above liquid in all tanks combined

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$$V_g := \frac{V_{gas}}{2}$$

Amount of vapor space volume per tank

$$V_{liq} := 10033 \cdot gal$$

This is the volume of liquid (V_{tks} - V_{sludge})

$$V_L := \frac{V_{liq}}{2}$$

This is the liquid volume split into 2 tanks

$$V_{tk} := \frac{V_{tks}}{2}$$

This is the total volume split into 2 tanks

$$M_{tk} := \frac{7348}{2} \cdot kg$$

Sludge Mass per tank

$$M := 7348 \cdot kg$$

Total Sludge

$$\rho_{GAC} := 500 \frac{gm}{L}$$

GAC density

$$\rho_{H2O} := 1 \frac{kg}{L}$$

Molecular Weights/Henry's Constants/Solid-Liquid Distribution

$$MW_{air} := 29 \frac{gm}{mol}$$

$$MW_{dcb} := 147 \frac{gm}{mol}$$

$$MW_{O2} := 32 \frac{gm}{mol}$$

$$MW_{TCE} := 131.4 \frac{gm}{mol}$$

$$MW_{Hg} := 200 \frac{gm}{mol}$$

$$MW_{H2O} := 18 \frac{gm}{mol}$$

$$H_{dcb} := 1.82 \frac{L \cdot atm}{mol}$$

$$H_{PCE} := 16.95 \frac{L \cdot atm}{mol}$$

$$MW_{PCE} := 166 \frac{gm}{mol}$$

$$H_{TCA} := 16.95 \frac{L \cdot atm}{mol}$$

$$H_{TCE} := 10 \frac{L \cdot atm}{mol}$$

$$MW_{TCA} := 133.5 \frac{gm}{mol}$$

$$H_{Aroclor1260} := \frac{1}{3.9 \frac{mol}{L \cdot atm}}$$

$$H_{Aroclor1260} = 2.56 \times 10^{-1} L \cdot \frac{atm}{mol}$$

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$$MW_{Aroclor1260} := (12 \cdot 12 + 5 + 5 \cdot 35.5) \frac{gm}{mol}$$

$$H_{Hg} := 10.75 \frac{L \cdot atm}{mol}$$

Determine the solid - liquid equilibrium constant (Hemond et al 1993)

$$k_D = K_{oc} \cdot f_{oc}$$

(From Hemond et al 1993)

$$\log(K_{oc}) = 0.544 \log(K_{ow}) + 1.377 \qquad \log(K_{ow}) = 2.5$$

Approximate average for PCE, TCA, and TCE, wide variety

$$K_{oc} := 10^{(0.544 \cdot 2.5 + 1.377)} \frac{mL}{gm} \qquad K_{oc} = 5.46 \times 10^2 \frac{L}{kg}$$

Determine the f_{oc} from the TOC:

$$TOC := 1.18 \, 10^5 \frac{mg}{kg} \qquad f_{oc} := TOC$$

Note, this has varied somewhat with different revs. The current TOC is 1.07 but the change is not that great so it is left at the conservative value, 1.18.

$$f_{oc} = 1.18 \times 10^{-1}$$

$$k_D := K_{oc} \cdot f_{oc} \qquad k_D = 6.44 \times 10^1 \frac{L}{kg}$$

For mercury:

$$k_{D\_Hg} := 52 \frac{mL}{gm} \qquad \text{(http://risk.lsd.ornl.gov/cgi-bin/tox/TOX\_select?select=nrad)}$$

For PCB (using Aroclor 1260)

$$K_{ow\_Aroclor1260} := 10^{6.5} \frac{L}{kg} \qquad \text{(From Hemond et al 1993)}$$

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$$K_{oc\_Ar} := 10^{\left(1.00 \cdot \log\left(\frac{K_{ow\_Aroclor1260}}{UnitsOf\left(K_{ow\_Aroclor1260}\right)}\right) - 0.21\right)} \frac{L}{kg} \qquad K_{oc\_Ar} = 1.95 \times 10^3 \frac{L}{kg}$$

$$k_{D\_Ar} := K_{oc\_Ar} \cdot f_{oc} \qquad\qquad k_{D\_Ar} = 2.3 \times 10^2 \frac{L}{kg}$$

Consolidation Tank

$$D_{imp} := 49 in \qquad\qquad N_{act} := 68 \frac{2 \cdot \pi}{min} \qquad\qquad Q_s := 40 \frac{ft^3}{min} \qquad\qquad \text{(Sparge)}$$

$$Q_v := 300 \frac{ft^3}{min} \qquad\qquad \textbf{V-Tank ventilation}$$

$$D_{tk} := 10 ft \qquad\qquad A_{tk} := \frac{\pi}{4} \cdot D_{tk}^2 \qquad\qquad Q_L := 2 \frac{ft^3}{min} \qquad\qquad \text{(In-Leakage)}$$

$$v_g := \frac{Q_s}{A_{tk}} \qquad\qquad v_g = 2.59 \times 10^{-3} \frac{m}{s} \qquad\qquad P_{ow\_act} := 3.5 hp \qquad \text{(Ashworth 2004b)}$$

$$\rho_g := \frac{P \cdot MW_{air}}{R_g \cdot T_g} \qquad\qquad \rho_g = 1.01 \frac{kg}{m^3} \qquad\qquad \rho_L := 1 \frac{kg}{L}$$

Derived Units/Miscellaneous

$$Ci := 3.7 \cdot 10^{10} s^{-1} \qquad \text{Curie definition} \qquad nCi := 10^{-9} Ci \qquad ppm_v := \frac{atm}{atm} \cdot 10^{-6}$$

$$\Delta t := 10 hr \qquad\qquad f_{safety} := 10 \qquad\qquad \infty_i := 10^6 hr \qquad \text{infinity practical definition}$$

Mass Transfer Correlations

$$b_1 := 0.026 W^{-0.4} \cdot m^{0.7} \cdot s^{-0.5} \qquad\qquad \text{(Perry et al 1984)}$$

$$b_2 := 0.002 W^{-0.7} \cdot m^{1.9} \cdot s^{-0.8}$$

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The liquid phase mass transfer coefficients are (Perry & Green 1984):

$$k_{La1} = b_1 \cdot \left(\frac{P_g}{V_{tk}}\right)^{0.4} \cdot v_g^{0.5} \qquad \text{For pure water/air}$$

$$k_{La2} = b2 \cdot \left(\frac{P_g}{V_{tk}}\right)^{0.7} \cdot v_g^{0.2} \qquad \text{For ionic solutions/air}$$

The P_g is the power reduced as a result of the air around the impeller. It is a function of the impeller diameter and the speed (Treybal 1987).

Let
$$\Xi := \frac{Q_s}{N_{act} \cdot D_{imp}^3} \qquad \Xi = 1.38 \times 10^{-3}$$

Conditional Statement for P_g

$$P_g := \left| \begin{array}{l} P_{ow\_act} \cdot (0.62 - 1.85\Xi) \quad \text{if } \Xi > 0.037 \\ P_{ow\_act} \cdot (1 - 12.2\Xi) \quad \text{otherwise} \end{array} \right. \qquad \text{Note, the } P_g \text{ is the "gassed" power}$$

$$P_g = 3.44 \text{hp}$$

$$k_{La1} := b_1 \cdot \left(\frac{P_g}{V_{tk}}\right)^{0.4} \cdot v_g^{0.5} \qquad k_{La1} = 8.76 \times 10^{-3} \, s^{-1}$$

$$k_{La2} := b_2 \cdot \left(\frac{P_g}{V_{tk}}\right)^{0.7} \cdot v_g^{0.2} \qquad k_{La2} = 1.66 \times 10^{-2} \, s^{-1}$$

Although the solid mass transfer is expected to be much higher than $k_L a$, there is still a certain degree of uncertainty. Therefore, use the worst case $k_L a$ of the above 2.

$$k_{La} := k_{La1} \qquad k_{La} = 8.76 \times 10^{-3} \, \frac{1}{s}$$

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Since this is for air, adjust for TCE related to the diffusivities in water for the two solutes by (Thibodeaux 1979, Crowl et al 1990):

$$\frac{k_{La\_dcb}}{k_{La\_air}} = \left(\frac{D_{dcb}}{D_{air}}\right)^{\frac{2}{3}} \qquad\qquad \frac{D_{dcb}}{D_{air}} = \sqrt{\frac{MW_{air}}{MW_{dcb}}}$$

$$k_{La\_dcb} := k_{La} \cdot \left(\frac{MW_{air}}{MW_{dcb}}\right)^{\frac{1}{3}} \qquad\qquad k_{La\_dcb} = 5.101 \times 10^{-3} \frac{1}{s}$$

$$k_{La\_PCE} := k_{La} \cdot \left(\frac{MW_{air}}{MW_{PCE}}\right)^{\frac{1}{3}} \qquad\qquad k_{La\_TCA} := k_{La} \cdot \left(\frac{MW_{air}}{MW_{TCA}}\right)^{\frac{1}{3}}$$

$$k_{La\_Hg} := k_{La} \cdot \left(\frac{MW_{air}}{MW_{Hg}}\right)^{\frac{1}{3}} \qquad\qquad k_{La\_TCE} := k_{La} \cdot \left(\frac{MW_{air}}{MW_{TCE}}\right)^{\frac{1}{3}}$$

$$k_{La\_Ar} := k_{La} \cdot \left(\frac{MW_{air}}{MW_{Aroclor1260}}\right)^{\frac{1}{3}}$$

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II. Characterization

To determine the applicable VOCs, data from two characterization reports (Tyson 2003, Tyson 2004) were used. However, these data needed to be filtered. The prescription used was to retain any component that had a detected concentration. For the V-tanks, this prescription was applicable for any tank in either phase. This was done at the 95% confidence level with the detect values used for any of the wastes where at least one detect value was listed (i.e., for the V-tanks, if one tank had an actual number where one or more of the other tanks had detect values, the detect values were averaged together with the actual numbers). This was done at the 95% confidence level using the Microsoft Excel function   TINV(probability, degrees of freedom).

$$C_i(95\%) = C_i + \text{TINV}(\Psi, df) \cdot \varepsilon_S$$

For the 2-tailed probability: $\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $\psi = 0.1$

The standard error, ε_S, and the degrees of freedom, df, were taken from the characterization reports (Tyson 2003 and Tyson 2004), where the second report accounts for the miscellaneous effluents that will be added. In general, the addition of these waste streams have a minor impact on the original characterization of the V-tanks, except for the additional TCA from ARA-16 that is approximately 25,000 mg/kg in the sludge. The report discussing these waste streams (Tyson 2004) provides weight-averages for the various detected constituents. Basically, the method follows:

1. Individual averages, standard errors, and degrees of freedoms were calculated for both sludge and liquid in all four V-tanks.

    Let the sludge phase concentrations of a component in Tank V-1 be represented by x_1, x_2, x_3, x_4, and x_5. In this instance, the sludge phase concentration for a component was represented in terms of an average x, a standard error s_e, and a degree of freedom equal to 4.

2. Calculate the weighted average concentrations for both sludge and liquid for the entire V-tank waste

From Step 1, individual components in each V-tank have an average concentration with a standard error and a degree of freedom. The weighted average was calculated using the volumes, densities, and the solids concentration in the sludge. Each of these parameters has average values with their own standard errors and degrees of freedom. The final weighted averages for a given component in the entire V-tank is then expressed as an average value with a calculated standard error and a calculated degree of freedom. Appendix B of Tyson 2003 shows how to calculate the standard error and degrees of freedom (propagation of error).

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3. Individual averages, standard errors, and degrees of freedoms were calculated for both sludge and liquid in all of the other waste steams that are to be added to the V-tank consolidation and treatment system.

4. Using the averages computed in Steps 2 and 3, calculate the overall composite waste stream weighted average, standard error, and degree of freedom for both phases. From these values, the 95% upper confidence limits for both liquid and sludge phase can be calculated as:

$$x_{95\%} = \bar{x} + s_e t$$

where t is a normal distribution value based on degrees of freedom and 95% upper limit.

The next filter consisted of finding the dimensionless form of Henry's Law and comparing it to 0.01 (http://www.cpeo.org/techtree/ttdescript/airstr.htm). If less, then the organic is considered SVOC and not included. For example, all of the phenols were filtered by this process as their H's were less than 0.01. The dimensionless form (H') is found by dividing the L-atm/mol form by RT. Note, this isn't a temperature correction. A temperature correction is given by Sander (Sander 1999).

$$H' = \frac{H(L*atm/mol))}{R(L*atm/mol/^\circ K)*T(298^\circ K)}$$

The following Table A.1 provides VOC data extracted from the characterization report (Tyson 2003 and 2004) and recent Henry's Law values along with their equilibrium vapor values (Sander 1999) It is provided as raw data.

Sander used k_H which is 1/H where H is the one used in this EDF and H' is the dimensionless form. The definition for Henry's Law for relating the gas partial pressure of a component to it's liquid phase concentration is:

$$p_i = \frac{1}{k_H} \cdot C_i = H \cdot C_i \qquad\qquad y_i = \frac{p_i}{P} = \frac{H \cdot C_i}{P}$$

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Table A.1

	MW	C_i, mg/L	C_i, mol/L	k_H, mol/L/atm	H, L-atm/mol	H'	p_i, atm	y_i, mol fr	y_i, ppm$_v$
Benzene	78.11	0.00E+00	0.00E+00	0.15	6.67	0.27	0.00E+00	0.00E+00	0.00
bromomethane	94.94	6.27E-01	6.60E-06	8.50E-02	11.76	0.48	7.77E-05	9.13E-05	91.25
Carbon disulfide	76.14	0.00E+00	0.00E+00	0.12	8.33	0.34	0.00E+00	0.00E+00	0.00
Chlorobenzene	112.56	0.00E+00	0.00E+00	0.55	1.82	0.07	0.00E+00	0.00E+00	0.00
Chloroethene (vinyl chloride)	62.50	1.04E+00	1.66E-05	0.30	3.33	0.14	5.54E-05	6.51E-05	65.12
chloromethane	50.49	1.07E-01	2.11E-06	0.23	4.35	0.18	9.19E-06	1.08E-05	10.80
1,2-dichlorobenzene	147.00	3.38E+00	2.30E-05	0.17	5.88	0.24	1.35E-04	1.59E-04	158.80
1,3-dichlorobenzene	147.00	3.44E+00	2.34E-05	0.13	7.69	0.31	1.80E-04	2.12E-04	211.58
1,4-dichlorobenzene	147.00	3.44E+00	2.34E-05	0.4	2.50	0.10	5.85E-05	6.88E-05	68.77
1,1-dichloroethane	98.96	3.32E-01	3.35E-06	0.059	16.95	0.69	5.68E-05	6.68E-05	66.76
cis-1,2-Dichloroethene	96.94	4.84E-03	4.99E-08	0.059	16.95	0.69	8.47E-07	9.95E-07	0.99
trans-1,2-dichloroethylene	96.94	5.76E-01	5.94E-06	0.46	2.17	0.09	1.29E-05	1.52E-05	15.19
1,1-Dichloroethene	96.94	1.74E-02	1.79E-07	0.1	10.00	0.41	1.79E-06	2.10E-06	2.10
Ethylbenzene	106.17	0.00E+00	0.00E+00	0.04	25.00	1.02	0.00E+00	0.00E+00	0.00
methylene chloride	84.93	1.15E+00	1.35E-05	0.36	2.78	0.11	3.76E-05	4.42E-05	44.19
4-Methyl-2-pentanone	100.16	0.00E+00	0.00E+00	2.20	0.45	0.02	0.00E+00	0.00E+00	0.00
Tetrachloroethylene (PCE)	165.83	1.37E+00	8.25E-06	0.06	16.95	0.69	1.40E-04	1.64E-04	164.38
Styrene	104.15	0.00E+00	0.00E+00	0.37	2.70	0.11	0.00E+00	0.00E+00	0.00
1,1,2,2-Tetrachloroethane	167.85	0.00E+00	0.00E+00	2.40	0.42	0.02	0.00E+00	0.00E+00	0.00
Toluene	92.14	5.29E-03	5.74E-08	0.16	6.25	0.26	3.59E-07	4.22E-07	0.42
1,2,4-Trichlorobenzene	181.45	3.43E+00	1.89E-05	0.46	2.17	0.09	4.11E-05	4.83E-05	48.31
1,1,2-Trichloroethane	133.40	2.08E-02	1.56E-07	1.10	0.91	0.04	1.42E-07	1.66E-07	0.17
1,1,1-Trichloroethane (TCA)	133.40	3.59E+00	2.69E-05	0.06	16.95	0.69	4.56E-04	5.36E-04	535.79
Trichloroethylene (TCE)	131.39	8.22E+00	6.26E-05	0.10	10.00	0.41	6.26E-04	7.35E-04	735.42
xylene	106.17	0.00E+00	0.00E+00	0.13	7.69	0.31	0.00E+00	0.00E+00	0.00
Hg	200	5.47E-02	2.73E-07	0.09	10.75	0.44	2.94E-06	3.46E-06	3.46

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III. Consolidation

III.1 Equilibrium of Weighted Average Tank Contents

Need the composition of the vapors using vapor-liquid-equilibria via Henry's Law. For Henry's Law to be valid, the water mole fraction needs to be near one. This isn't strictly true in this case but the results are believed to be conservative. Also, it is assumed that the equilibria is water-gas and the other phases (e.g., TCE-sludge) do not contribute. This is a typical assumption, i.e., using the top or continuous phase for emission properties (http://www.epa.gov/ttn/chief/faq/tanksfaq.html). These are simply the values in Table A.1 for the composite, weighted-average V-Tank VOCs and Hg.

III.2 Transient and Steady-State VOC Concentrations During Consolidation

III.2.1   **Problem Statement**
III.2.2   **Derivation of Model**
III.2.3   **Data**
III.2.3.a V_x **Worse Case**
III.2.3.b V_9 **Worse Case**
III.2.3.c   **Consolidation Tanks**
III.2.4   **Results**
III.2.4.a   **Vx Results**
III.2.4.b   **V9 Results**
III.2.4.c   **Consolidation Tank Results**

III.2.1   **Problem Statement**
Determine vapor phase concentrations of PCE, TCA, TCE, and Hg with no mitigation during V-Tank Consolidation. The figure below (Figure A.1) shows the configuration. Initially, the V-Tank vapor is at equilibrium at t = 0. This is soon diluted by the incoming air and reduced to near zero. The wand at the left indicates energy input that will impact the mass transfer coefficient. The consolidation tank is assumed to be always at equilibrium while filling, the highest concentration possible in the vapor phase. Figure A.2 shows cross sections for velocity determination used for mass transfer purposes. These calculations are used for the consolidation design flowsheet.
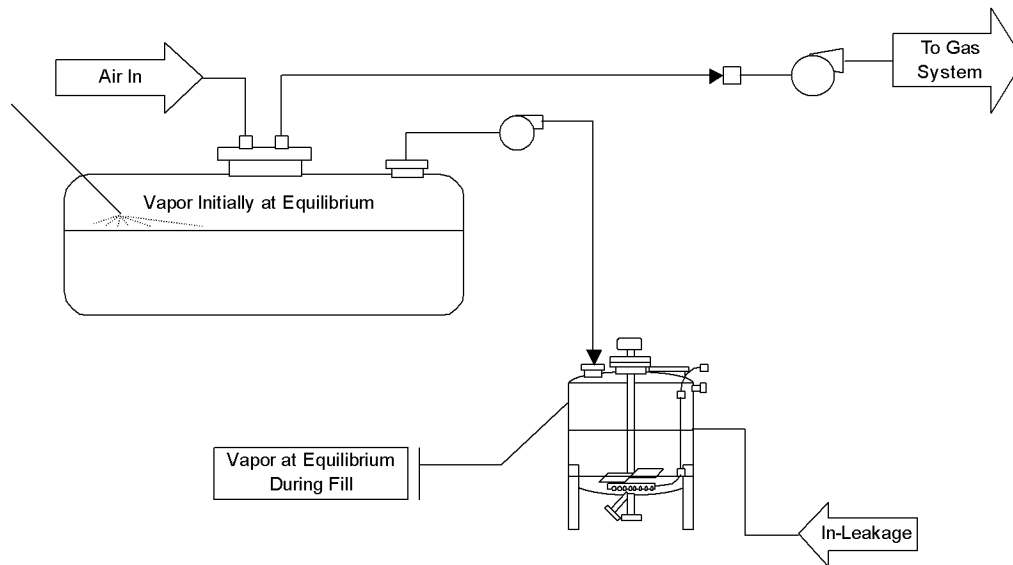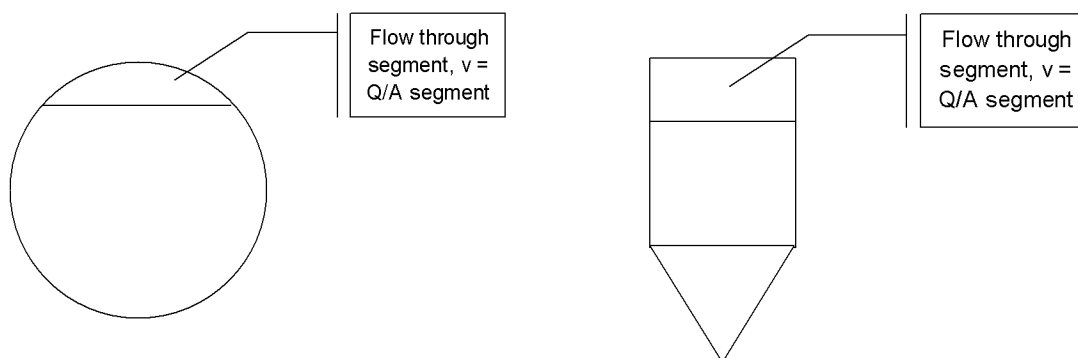
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Figure A.1

Figure A.2

III.2.2   Derivation of Model

2 differentials to solve

$$V_g \cdot \left(\frac{d}{dt} C_g \right) = K \cdot A \cdot \left(C_L - \frac{p}{H} \right) - Q \cdot C_g$$

Balance on the vapor space

$$V_L \cdot \left(\frac{d}{dt} C_L \right) = -K \cdot A \cdot \left(C_L - \frac{p}{H} \right)$$

Balance on the liquid space (as explained in Appendix B)

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Solve the 2nd to put into the first assuming p/H is zero (worse case)

$$C_L = C_{Lo} \cdot e^{\frac{-K \cdot A}{V_L} \cdot t}$$

Resulting in:

$$\frac{d}{dt} C_g + \frac{Q}{V_g} \cdot C_g = \frac{K \cdot A \cdot C_{Lo}}{V_g} \cdot e^{\frac{-K \cdot A}{V_L} \cdot t}$$

Solving via an integrating factor:

$$I = e^{\int \frac{Q}{V_g} dt} \qquad\qquad I = \exp\left(\frac{Q}{V_g} \cdot t\right)$$

Multiply both sides by I

$$e^{\left(\frac{Q}{V_g} \cdot t\right)} \cdot \frac{d}{dt} C_g + \frac{Q}{V_g} \cdot C_g \cdot e^{\left(\frac{Q}{V_g} \cdot t\right)} = \frac{K \cdot A \cdot C_{Lo}}{V_g} \cdot e^{\frac{-K \cdot A}{V_L} \cdot t} \cdot e^{\left(\frac{Q}{V_g} \cdot t\right)}$$

$$\frac{d}{dt}\left[C_g \cdot e^{\left(\frac{Q}{V_g} \cdot t\right)} \right] = \frac{K \cdot A \cdot C_{Lo}}{V_g} \cdot e^{\frac{-K \cdot A}{V_L} \cdot t} \cdot e^{\left(\frac{Q}{V_g} \cdot t\right)}$$

$$C_g \cdot e^{\left(\frac{Q}{V_g} \cdot t\right)} = \int \frac{K \cdot A \cdot C_{Lo}}{V_g} \cdot e^{\frac{-K \cdot A}{V_L} \cdot t} \cdot e^{\left(\frac{Q}{V_g} \cdot t\right)} dt$$

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$$C_g \cdot \exp\left(\frac{Q}{V_g} \cdot t\right) = \frac{1}{-K \cdot \frac{A}{V_L} + \frac{Q}{V_g}} \cdot \exp\left(-K \cdot \frac{A}{V_L} \cdot t + \frac{Q}{V_g} \cdot t\right) \cdot K \cdot A \cdot \frac{C_{Lo}}{V_g} + const$$

$$C_g = \frac{\dfrac{1}{-K \cdot \dfrac{A}{V_L} + \dfrac{Q}{V_g}} \cdot \exp\left(-K \cdot \dfrac{A}{V_L} \cdot t + \dfrac{Q}{V_g} \cdot t\right) \cdot K \cdot A \cdot \dfrac{C_{Lo}}{V_g}}{\exp\left(\dfrac{Q}{V_g} \cdot t\right)} + \frac{const}{\exp\left(\dfrac{Q}{V_g} \cdot t\right)}$$

$$C_g = \frac{V_L}{-K \cdot A \cdot V_g + Q \cdot V_L} \cdot K \cdot A \cdot C_{Lo} \cdot \exp\left(-K \cdot \frac{A}{V_L} \cdot t\right) + \frac{const}{\exp\left(\dfrac{Q}{V_g} \cdot t\right)}$$

at t = 0, $C_g = C_{go}$

$$const = C_{go} - \frac{V_L}{-K \cdot A \cdot V_g + Q \cdot V_L} \cdot K \cdot A \cdot C_{Lo}$$

$$C_g = \frac{V_L}{-K \cdot A \cdot V_g + Q \cdot V_L} \cdot K \cdot A \cdot C_{Lo} \cdot e^{\left(-K \cdot \frac{A}{V_L} \cdot t\right)} + \left(C_{go} - \frac{V_L}{-K \cdot A \cdot V_g + Q \cdot V_L} \cdot K \cdot A \cdot C_{Lo}\right) \cdot e^{-\left(\frac{Q}{V_g} \cdot t\right)}$$

simplify equation by

$$\alpha = \frac{V_L}{-K \cdot A \cdot V_g + Q \cdot V_L} \cdot K \cdot A \cdot C_{Lo} \qquad\qquad \beta = -K \cdot \frac{A}{V_L} \qquad\qquad \gamma = -\frac{Q}{V_g}$$

$$C_g = \alpha \cdot e^{\beta \cdot t} + \left(C_{go} - \alpha\right) \cdot e^{\gamma \cdot t}$$

The mass transfer coefficient, K, is a function of velocity, T, and energy from the hosing and jostling, etc (f_{safety}). This is not easily correlated so a safety factor is used.

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$$K = f\left(v, T, f_{safety}\right)$$

To find the velocity, it is the Q/A of the segment shown below for V-1, -2, and -3.

For oxygen, a tank test coefficient with wave action (an analagous situation) coefficient is given by Thibodeaux 1979 vs. wind speed. The coefficient is based on the figure below (Figure A.3):

Figure A.3
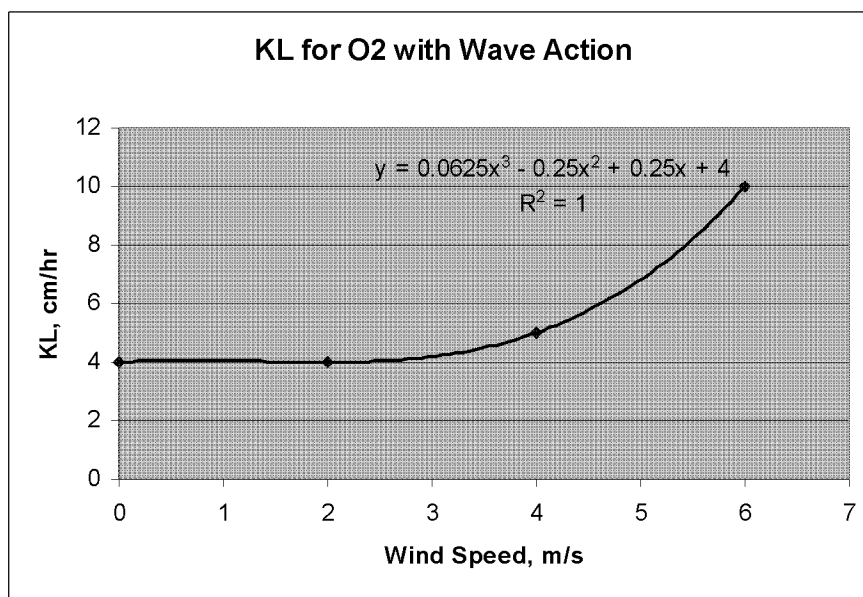
It has an assymtope at 4 cm/s and will apply for all cases since the velocity is so low. For various situations, the K needs adjustment for different molecules and as a function of temperature.

Boundary layer theory suggests the following relation between K and diffusivity (Thibodeaux 1979):

$$K_2 = K_1 \cdot \left(\frac{D_2}{D_1}\right)^{\frac{2}{3}}$$

According to Graham's Law of diffusuion:

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$$\frac{D_2}{D_1} = \left(\frac{MW_1}{MW_2}\right)^{\frac{1}{2}} \qquad \text{Leading to:} \qquad K_2 = K_1 \cdot \left(\frac{MW_1}{MW_2}\right)^{\frac{1}{3}}$$

$$K_{O2} := 4\,\frac{cm}{hr} \qquad\qquad K_i = K_{O2} \cdot \left(\frac{MW_{O2}}{MW_i}\right)^{\frac{1}{3}}$$

According to BSL (Bird et al 1960) diffusion and hence K is 1st order in temperature and viscosity. However, the viscosity of liquid is exponential in temperature so use a viscosity ratio for V-9.

$$\mu = \left(\frac{\delta}{a}\right)^2 \cdot \frac{N_{AV} \cdot h}{V_m} \cdot e^{\frac{\Delta G_0}{RT}}$$

$$T_{amb} := 298K$$

Assuming all of the other items stay constant:

$$\frac{\mu_1}{\mu_2} = e^{\frac{\Delta G_0}{R} \cdot \left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

The $\Delta G/R$ has been found by experiment (Bird et al) to be 3.8 x boiling temperature. The entire correction from oxygen to i and using a correction and safety factor is:

$$K_i = K_{O2} \cdot \frac{T_2}{T_1} \cdot \left(\frac{MW_{O2}}{MW_i}\right)^{\frac{1}{3}} \cdot e^{3.8 \cdot T_b \cdot \left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

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III.2.3   Data

III.2.3a V_x Worse Case

The air in-leakage flow to the Vx tanks should be no greater than the V9:

$$Q_{a9} := 191 \frac{ft^3}{min} \qquad \text{From EXCEL vaccum balance and all standard}$$

$$Q_{ax} := Q_{a9}$$

$$A_{seg} = r^2 \cdot acos\left(\frac{r-H}{r}\right) - (r-H)\cdot\sqrt{2\cdot r\cdot H - H^2}$$

Since there are velocity and area effects, use the mid point for V_x, simplifying the area to $\pi D^2/8$

$$D_{Vx} := 10 ft \qquad A_{cx} := \frac{\pi}{8}\cdot D_{Vx}^2 \qquad A_{cx} = 3.93\times 10^1 ft^2$$

$$v := \frac{Q_{ax}}{A_{cx}} \qquad v = 8.11\times 10^{-2}\frac{ft}{s} \qquad v = 2.47\times 10^{-2}\frac{m}{s}$$

As this is less than 3 m/s, the assymtope is used and K is same for both tanks except for T correction.

$$L_x := 19.7 ft$$

Volumes

$$V_{Lx} := \frac{1}{2}\cdot\frac{\pi}{4}\cdot D_{Vx}^2\cdot L_x \qquad V_{Lx} = 5.79\times 10^3 gal \qquad V_{gx} := V_{Lx}$$

Need a reasonable time to remove a V_x tank, say 24 hr:

$$\tau_x := 24 hr$$

The mass transfer area is based on the plan view:

$$A_{ix} := 10 ft\cdot 19.5 ft \qquad A_{ix} = 1.95\times 10^2 ft^2$$

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$T_x := 298 K$

Concentrations (Tyson 2004)

	V-Tank Liquid Compositions @95%UCL, mg/L			
Constituent	V-1	V-2	V-3	V-9
PCE	2.11E-01	4.18E-02	4.16E-02	7.29E+01
TCA	4.18E-02	4.18E-02	4.16E-02	1.80E+02
TCE	2.41E-01	4.52E-01	3.00E-01	6.36E+02
Hg	4.02E-01	4.18E-03	4.16E-03	0.563

$$C_{LoPCEx} := 0.211 \frac{mg}{L} \qquad C_{LoTCAx} := .0418 \frac{mg}{L} \qquad C_{LoTCEx} := 0.452 \frac{mg}{L}$$

$$C_{LoHgx} := 0.402 \frac{mg}{L}$$

$$P_{PCEx} := H_{PCE} \frac{C_{LoPCEx}}{MW_{PCE}} \qquad\qquad P_{PCEx} = 2.15 \times 10^{-5} \, atm$$

$$C_{goPCEx} := \frac{P_{PCEx} \cdot MW_{TCE}}{R_g \cdot T_x} \qquad\qquad C_{goPCEx} = 1.16 \times 10^{-1} \frac{mg}{L}$$

$$C_{goPCEx\_ppm} := \frac{C_{goPCEx}}{MW_{PCE}} \cdot R_{star} \cdot 10^6 \qquad\qquad C_{goPCEx\_ppm} = 1.56 \times 10^1$$

$$P_{TCAx} := H_{TCA} \cdot \frac{C_{LoTCAx}}{MW_{TCA}} \qquad\qquad P_{TCAx} = 5.31 \times 10^{-6} \, atm$$

$$C_{goTCAx} := \frac{P_{TCAx} \cdot MW_{TCA}}{R_g \cdot T_x} \qquad\qquad C_{goTCAx} = 2.9 \times 10^{-2} \frac{mg}{L}$$

$$C_{goTCAx\_ppm} := \frac{C_{goTCAx}}{MW_{TCA}} \cdot R_{star} \cdot 10^6 \qquad\qquad C_{goTCAx\_ppm} = 4.86 \times 10^0$$

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$$p_{TCEx} := H_{TCE} \frac{C_{LoTCEx}}{MW_{TCE}}$$

$$p_{TCEx} = 3.44 \times 10^{-5} \, atm$$

$$C_{goTCEx} := \frac{p_{TCEx} MW_{TCE}}{R_g \cdot T_x}$$

$$C_{goTCEx} = 1.85 \times 10^{-1} \frac{mg}{L}$$

$$C_{goTCEx\_ppm} := \frac{C_{goTCEx}}{MW_{TCE}} \cdot R_{star} \cdot 10^6$$

$$C_{goTCEx\_ppm} = 3.15 \times 10^1$$

$$p_{Hgx} := H_{Hg} \cdot \frac{C_{LoHgx}}{MW_{Hg}}$$

$$p_{Hgx} = 2.16 \times 10^{-5} \, atm$$

$$C_{goHgx} := \frac{p_{Hgx} \cdot MW_{Hg}}{R_g \cdot T_x}$$

$$C_{goHgx} = 1.77 \times 10^{-1} \frac{mg}{L}$$

$$C_{goHgx\_ppm} := \frac{C_{goHgx}}{MW_{Hg}} \cdot R_{star} \cdot 10^6$$

$$C_{goHgx\_ppm} = 1.98 \times 10^1$$

According to BSL (Bird et al 1960) diffusion and hence K is 1st order in temperature and a function of viscosity. Since this is assumed ambient, there is no adjustment. Therefore, the final, adjusted K is:

$$K_{PCEx} := K_{O2} \left(\frac{MW_{O2}}{MW_{PCE}} \right)^{\frac{1}{3}} \cdot f_{safety}$$

$$K_{PCEx} = 6.42 \times 10^{-5} \frac{m}{s}$$

$$K_{TCAx} := K_{O2} \left(\frac{MW_{O2}}{MW_{TCA}} \right)^{\frac{1}{3}} \cdot f_{safety}$$

$$K_{TCAx} = 6.9 \times 10^{-5} \frac{m}{s}$$

$$K_{TCEx} := K_{O2} \left(\frac{MW_{O2}}{MW_{TCE}} \right)^{\frac{1}{3}} \cdot f_{safety}$$

$$K_{TCEx} = 6.94 \times 10^{-5} \frac{m}{s}$$

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$$K_{Hgx} := K_{O2} \cdot \left(\frac{MW_{O2}}{MW_{Hg}} \right)^{\frac{1}{3}} \cdot f_{safety} \qquad\qquad K_{Hgx} = 6.03 \times 10^{-5} \, \frac{m}{s}$$

$$\gamma_x := -\frac{Q_{ax}}{V_{gx}} \qquad\qquad \gamma'_x = -2.47 \times 10^{-1} \, \frac{1}{min}$$

$$\alpha_{PCEx} := \frac{V_{Lx}}{-K_{PCEx} \cdot A_{ix} \cdot V_{gx} + Q_{ax} \cdot V_{Lx}} \cdot K_{PCEx} \cdot A_{ix} \cdot C_{LoPCEx} \qquad\qquad \alpha_{PCEx} = 2.76 \times 10^{-3} \, \frac{mg}{L}$$

$$\beta_{PCEx} := -K_{PCEx} \cdot \frac{A_{ix}}{V_{Lx}} \qquad\qquad \beta_{PCEx} = -3.18 \times 10^{-3} \, \frac{1}{min}$$

$$\alpha_{TCAx} := \frac{V_{Lx}}{-K_{TCAx} \cdot A_{ix} \cdot V_{gx} + Q_{ax} \cdot V_{Lx}} \cdot K_{TCAx} \cdot A_{ix} \cdot C_{LoTCAx} \qquad\qquad \alpha_{TCAx} = 5.88 \times 10^{-4} \, \frac{mg}{L}$$

$$\beta_{TCAx} := -K_{TCAx} \cdot \frac{A_{ix}}{V_{Lx}} \qquad\qquad \beta_{TCAx} = -3.42 \times 10^{-3} \, \frac{1}{min}$$

$$\alpha_{TCEx} := \frac{V_{Lx}}{-K_{TCEx} \cdot A_{ix} \cdot V_{gx} + Q_{ax} \cdot V_{Lx}} \cdot K_{TCEx} \cdot A_{ix} \cdot C_{LoTCEx} \qquad\qquad \alpha_{TCEx} = 6.39 \times 10^{-3} \, \frac{mg}{L}$$

$$\beta_{TCEx} := -K_{TCEx} \cdot \frac{A_{ix}}{V_{Lx}} \qquad\qquad \beta_{TCEx} = -3.44 \times 10^{-3} \, \frac{1}{min}$$

$$\alpha_{Hgx} := \frac{V_{Lx}}{-K_{Hgx} \cdot A_{ix} \cdot V_{gx} + Q_{ax} \cdot V_{Lx}} \cdot K_{Hgx} \cdot A_{ix} \cdot C_{LoHgx} \qquad\qquad \alpha_{Hgx} = 4.93 \times 10^{-3} \, \frac{mg}{L}$$

$$\beta_{Hgx} := -K_{Hgx} \cdot \frac{A_{ix}}{V_{Lx}} \qquad\qquad \beta_{Hgx} = -2.99 \times 10^{-3} \, \frac{1}{min}$$

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III.2.3.b V9 Worse Case

$$T_9 := (460 + 170)R \qquad\qquad T_9 = 3.5 \times 10^2 \, K$$

$$V_{L9} := \frac{70}{2} \, gal$$

Since volumes change with time, use average to simplify

$$V_{L9T} := 320 \, gal \qquad\qquad V_{g9} := \frac{400}{2} \, gal$$

	V-Tank Liquid Compositions @95%UCL, mg/L			
Constituent	V-1	V-2	V-3	V-9
PCE	2.11E-01	4.18E-02	4.16E-02	7.29E+01
TCA	4.18E-02	4.18E-02	4.16E-02	1.80E+02
TCE	2.41E-01	4.52E-01	3.00E-01	6.36E+02
Hg	4.02E-01	4.18E-03	4.16E-03	0.563

$$C_{LoPCE9} := 72.9 \frac{mg}{L} \qquad C_{LoTCA9} := 180 \frac{mg}{L} \qquad C_{LoTCE9} := 636 \frac{mg}{L}$$

$$C_{LoHg9} := 0.563 \frac{mg}{L}$$

$$p_{PCE9} := H_{PCE} \frac{C_{LoPCE9}}{MW_{PCE}} \qquad\qquad p_{PCE9} = 7.44 \times 10^{-3} \, atm$$

$$C_{goPCE9} := \frac{p_{PCE9} MW_{TCE}}{R_g \cdot T_9} \qquad\qquad C_{goPCE9} = 3.41 \times 10^1 \frac{mg}{L}$$

$$C_{goPCE9\_ppm} := \frac{C_{goPCE9}}{MW_{PCE}} \cdot R_{star} \cdot 10^6 \qquad\qquad C_{goPCE9\_ppm} = 4.6 \times 10^3$$

$$p_{TCA9} := H_{TCA} \cdot \frac{C_{LoTCA9}}{MW_{TCA}} \qquad\qquad p_{TCA9} = 2.29 \times 10^{-2} \, atm$$

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$$C_{goTCA9} := \frac{P_{TCA9} \cdot MW_{TCA}}{R_g \cdot T_9}$$

$$C_{goTCA9} = 1.06 \times 10^2 \frac{mg}{L}$$

$$C_{goTCA9\_ppm} := \frac{C_{goTCA9}}{MW_{TCA}} \cdot R_{star} \cdot 10^6$$

$$C_{goTCA9\_ppm} = 1.78 \times 10^4$$

$$P_{TCE9} := H_{TCE} \frac{C_{LoTCE9}}{MW_{TCE}}$$

$$P_{TCE9} = 4.84 \times 10^{-2} atm$$

$$C_{goTCE9} := \frac{P_{TCE9} MW_{TCE}}{R_g \cdot T_9}$$

$$C_{goTCE9} = 2.22 \times 10^2 \frac{mg}{L}$$

$$C_{goTCE9\_ppm} := \frac{C_{goTCE9}}{MW_{TCE}} \cdot R_{star} \cdot 10^6$$

$$C_{goTCE9\_ppm} = 3.78 \times 10^4$$

$$P_{Hg9} := H_{Hg} \cdot \frac{C_{LoHg9}}{MW_{Hg}}$$

$$P_{Hg9} = 3.03 \times 10^{-5} atm$$

$$C_{goHg9} := \frac{P_{Hg9} \cdot MW_{Hg}}{R_g \cdot T_9}$$

$$C_{goHg9} = 2.11 \times 10^{-1} \frac{mg}{L}$$

$$C_{goHg9\_ppm} := \frac{C_{goHg9}}{MW_{Hg}} \cdot R_{star} \cdot 10^6$$

$$C_{goHg9\_ppm} = 2.36 \times 10^1$$

The boiling points are from Lange's (Dean 1985):

$$T_{bPCE} := (121 + 273)K \qquad T_{bTCA} := (74 + 273)K$$

$$T_{bTCE} := (273 + 87)K \qquad T_{bHg} := (273 + 357)K$$

Find the viscosity ratios:

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$$\mu_{rat\_PCE} := e^{3.8 \cdot T_{bPCE} \cdot \left(\frac{1}{T_{amb}} - \frac{1}{T_9} \right)} \qquad\qquad \mu_{rat\_PCE} = 2.11 \times 10^0$$

$$\mu_{rat\_TCA} := e^{3.8 \cdot T_{bTCA} \cdot \left(\frac{1}{T_{amb}} - \frac{1}{T_9} \right)} \qquad\qquad \mu_{rat\_TCA} = 1.93 \times 10^0$$

$$\mu_{rat\_TCE} := e^{3.8 \cdot T_{bTCE} \cdot \left(\frac{1}{T_{amb}} - \frac{1}{T_9} \right)} \qquad\qquad \mu_{rat\_TCE} = 1.98 \times 10^0$$

$$\mu_{rat\_Hg} := e^{3.8 \cdot T_{bHg} \cdot \left(\frac{1}{T_{amb}} - \frac{1}{T_9} \right)} \qquad\qquad \mu_{rat\_Hg} = 3.3 \times 10^0$$

Therefore, the final, adjusted K is:

$$K_{PCE9} := K_{O2} \cdot \left(\frac{MW_{O2}}{MW_{PCE}} \right)^{\frac{1}{3}} \cdot f_{safety} \cdot \left(\frac{T_9}{T_{amb}} \right) \cdot \mu_{rat\_PCE} \qquad\qquad K_{PCE9} = 1.59 \times 10^{-4} \frac{m}{s}$$

$$K_{TCA9} := K_{O2} \cdot \left(\frac{MW_{O2}}{MW_{TCA}} \right)^{\frac{1}{3}} \cdot f_{safety} \cdot \left(\frac{T_9}{T_{amb}} \right) \cdot \mu_{rat\_TCA} \qquad\qquad K_{TCA9} = 1.56 \times 10^{-4} \frac{m}{s}$$

$$K_{TCE9} := K_{O2} \cdot \left(\frac{MW_{O2}}{MW_{TCE}} \right)^{\frac{1}{3}} \cdot f_{safety} \cdot \left(\frac{T_9}{T_{amb}} \right) \cdot \mu_{rat\_TCE} \qquad\qquad K_{TCE9} = 1.61 \times 10^{-4} \frac{m}{s}$$

$$K_{Hg9} := K_{O2} \cdot \left(\frac{MW_{O2}}{MW_{Hg}} \right)^{\frac{1}{3}} \cdot f_{safety} \cdot \left(\frac{T_9}{T_{amb}} \right) \cdot \mu_{rat\_Hg} \qquad\qquad K_{Hg9} = 2.34 \times 10^{-4} \frac{m}{s}$$

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Need to determine a reasonable time to remove V-9, say 4 hr

$$\tau_9 := 4\text{hr} \qquad\qquad\qquad \tau_9 = 1.44 \times 10^4 \, s$$

assume 4 x volume generated during removal $\qquad V_9 := 4 \cdot V_{L9T}$

$$D_{V9} := 42\text{in}$$

$$A_{i9} := \frac{\pi}{4} \cdot D_{V9}^2 \qquad\qquad\qquad A_{i9} = 9.62 \times 10^0 \, ft^2$$

The flow is less than the V_x tanks since it's going through a 6 in nozzle

$$L_i := 3\text{ft} \qquad\qquad\qquad \text{The height above the liquid level}$$

$$r := \frac{D_{V9}}{2} \qquad\qquad \text{The area for finding the average velocity is:} \qquad r = 5.33 \times 10^{-1} \, m$$

$$A_{avev} = 2 \cdot \sqrt{r^2 - x^2} \cdot L \qquad\qquad\qquad \frac{d}{dx}\left(2 \cdot \sqrt{r^2 - x^2} \cdot L\right) = \frac{-2}{\sqrt{r^2 - x^2}} \cdot L \cdot x$$

$$v_9 := \frac{\displaystyle\int_{0.533m}^{0} \frac{Q_{a9}}{\left(2 \cdot \sqrt{r^2 - x^2} \cdot L_i\right)} \cdot \left(\frac{-2}{\sqrt{r^2 - x^2}} \cdot L_i \cdot x\right) dx}{\displaystyle\int_{0.533m}^{0} \left(\frac{-2}{\sqrt{r^2 - x^2}} \cdot L_i \cdot x\right) dx} \qquad\qquad v_9 = 3.13 \times 10^{-1} \frac{m}{s}$$

$$v_9 := \frac{Q_{a9}}{A_{i9}} \qquad\qquad\qquad v_9 = 3.13 \times 10^{-1} \frac{m}{s}$$

$$\gamma_9 := -\frac{Q_{a9}}{V_{g9}} \qquad\qquad\qquad \gamma_9' = -7.14 \times 10^0 \frac{1}{min}$$

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$$\alpha_{PCE9} := \frac{V_{L9}}{-K_{PCE9} A_{i9} \cdot V_{g9} + Q_{a9} \cdot V_{L9}} \cdot K_{PCE9} A_{i9} \cdot C_{LoPCE9} \qquad \alpha_{PCE9} = 1.16 \times 10^{-1} \frac{mg}{L}$$

$$\beta_{PCE9} := -K_{PCE9} \frac{A_{i9}}{V_{L9}} \qquad \beta_{PCE9} = -6.44 \times 10^{-2} \frac{1}{min}$$

$$\alpha_{TCA9} := \frac{V_{L9}}{-K_{TCA9} \cdot A_{i9} \cdot V_{g9} + Q_{a9} \cdot V_{L9}} \cdot K_{TCA9} \cdot A_{i9} \cdot C_{LoTCA9} \qquad \alpha_{TCA9} = 2.82 \times 10^{-1} \frac{mg}{L}$$

$$\beta_{TCA9} := -K_{TCA9} \cdot \frac{A_{i9}}{V_{L9}} \qquad \beta_{TCA9} = -6.33 \times 10^{-2} \frac{1}{min}$$

$$\alpha_{TCE9} := \frac{V_{L9}}{-K_{TCE9} A_{i9} \cdot V_{g9} + Q_{a9} \cdot V_{L9}} \cdot K_{TCE9} A_{i9} \cdot C_{LoTCE9} \qquad \alpha_{TCE9} = 1.03 \times 10^{0} \frac{mg}{L}$$

$$\beta_{TCE9} := -K_{TCE9} \frac{A_{i9}}{V_{L9}} \qquad \beta_{TCE9} = -6.52 \times 10^{-2} \frac{1}{min}$$

$$\alpha_{Hg9} := \frac{V_{L9}}{-K_{Hg9} \cdot A_{i9} \cdot V_{g9} + Q_{a9} \cdot V_{L9}} \cdot K_{Hg9} \cdot A_{i9} \cdot C_{LoHg9} \qquad \alpha_{Hg9} = 1.32 \times 10^{-3} \frac{mg}{L}$$

$$\beta_{Hg9} := -K_{Hg9} \cdot \frac{A_{i9}}{V_{L9}} \qquad \beta_{Hg9} = -9.46 \times 10^{-2} \frac{1}{min}$$

III.2.4. Results

III.2.4.a V_x Results

The amount coming from V-x tanks is initially at equilibrium then falls off and becomes zero once all of the contents have been removed.

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PCE/Vx Results

Concentration vs. time:

$$C_{PCEx}(t) := \frac{R_{star}}{MW_{PCE}} \cdot \left[\alpha_{PCEx} \cdot e^{\beta_{PCEx} \cdot t} + \left(C_{goPCEx} - \alpha_{PCEx}\right) \cdot e^{\gamma_x \cdot t} \right] \cdot \Phi\left(\tau_x - t\right)$$

$$C_{PCEx}(0hr) = 1.56 \times 10^1 \, ppm_v \qquad\qquad C_{PCEx}\left(\infty_i\right) = 0 \times 10^0$$

The time weighted average (if $\tau_x > \Delta t$, use Δt):

$$TWA_{PCEx} := \frac{R_{star}}{MW_{PCE} \cdot \Delta t} \cdot \int_0^{\Delta t} \left[\alpha_{PCEx} \cdot e^{\beta_{PCEx} \cdot t} + \left(C_{goPCEx} - \alpha_{PCEx}\right) \cdot e^{\gamma_x \cdot t} \right] dt$$

$$TWA_{PCEx} = 2.69 \times 10^{-1} \, ppm_v$$

The total amount over the run time:

$$m_{PCEx} := \int_0^{\tau_x} \left[\alpha_{PCEx} \cdot e^{\beta_{PCEx} \cdot t} + \left(C_{goPCEx} - \alpha_{PCEx}\right) \cdot e^{\gamma_x \cdot t} \right] \cdot Q_{ax} \, dt$$

$$m_{PCEx} = 7.11 \times 10^{-3} \, kg$$

TCA/Vx Results

Concentration vs. time:

$$C_{TCAx}(t) := \frac{R_{star}}{MW_{TCA}} \cdot \left[\alpha_{TCAx} \cdot e^{\beta_{TCAx} \cdot t} + \left(C_{goTCAx} - \alpha_{TCAx}\right) \cdot e^{\gamma_x \cdot t} \right] \cdot \Phi\left(\tau_x - t\right)$$

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$$C_{TCAx}(0hr) = 4.86 \times 10^0 \, ppm_v \qquad\qquad C_{TCAx}(\infty_i) = 0 \times 10^0$$

The time weighted average:

$$TWA_{TCAx} := \frac{R_{star}}{MW_{TCA} \cdot \Delta t} \cdot \int_0^{\Delta t} \left[\alpha_{TCAx} \cdot e^{\beta_{TCAx} \cdot t} + \left(C_{goTCAx} - \alpha_{TCAx} \right) \cdot e^{\gamma_x \cdot t} \right] dt$$

$$TWA_{TCAx} = 7.4 \times 10^{-2} \, ppm_v$$

The total amount over the run time:

$$m_{TCAx} := \int_0^{\tau_9} \left[\left[\alpha_{TCAx} \cdot e^{\beta_{TCAx} \cdot t} + \left(C_{goTCAx} - \alpha_{TCAx} \right) \cdot e^{\gamma_x \cdot t} \right] \cdot Q_{ax} \right] dt$$

$$m_{TCAx} = 1.14 \times 10^{-3} \, kg$$

TCE/Vx Results

Concentration vs. time:

$$C_{TCEx}(t) := \frac{R_{star}}{MW_{TCE}} \cdot \left[\alpha_{TCEx} \cdot e^{\beta_{TCEx} \cdot t} + \left(C_{goTCEx} - \alpha_{TCEx} \right) \cdot e^{\gamma_x \cdot t} \right] \cdot \Phi\left(\tau_x - t\right)$$

$$C_{TCEx}(0hr) = 3.15 \times 10^1 \, ppm_v \qquad\qquad C_{TCEx}(\infty_i) = 0 \times 10^0$$

The time weighted average:

$$TWA_{TCEx} := \frac{R_{star}}{MW_{TCE} \cdot \Delta t} \cdot \int_0^{\Delta t} \left[\alpha_{TCEx} \cdot e^{\beta_{TCEx} \cdot t} + \left(C_{goTCEx} - \alpha_{TCEx} \right) \cdot e^{\gamma_x \cdot t} \right] dt$$

$$TWA_{TCEx} = 6.66 \times 10^{-1} \, ppm_v$$

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The total amount over the run time:

$$m_{TCEx} := \int_0^{\tau_x} \left[\alpha_{TCEx} \cdot e^{\beta_{TCEx} \cdot t} + \left(C_{goTCEx} - \alpha_{TCEx} \right) \cdot e^{\gamma_x \cdot t} \right] \cdot Q_{ax} \, dt$$

$$m_{TCEx} = 1.39 \times 10^{-2} \, kg$$

Hg/Vx Results

Concentration vs. time:

$$C_{Hgx}(t) := \left[\alpha_{Hgx} \cdot e^{\beta_{Hgx} \cdot t} + \left(C_{goHgx} - \alpha_{Hgx} \right) \cdot e^{\gamma_x \cdot t} \right] \cdot \Phi \left(\tau_x - t \right)$$

$$C_{Hgx}(0hr) = 1.77 \times 10^2 \, \frac{mg}{m^3} \qquad\qquad C_{Hgx}\left(\infty_i \right) = 0 \times 10^0 \, \frac{mg}{m^3}$$

The time weighted average:

$$TWA_{Hgx} := \frac{1}{\Delta t} \cdot \int_0^{\Delta t} \left[\alpha_{Hgx} \cdot e^{\beta_{Hgx} \cdot t} + \left(C_{goHgx} - \alpha_{Hgx} \right) \cdot e^{\gamma_x \cdot t} \right] dt$$

$$TWA_{Hgx} = 3.45 \times 10^0 \, \frac{mg}{m^3}$$

The total amount over the run time:

$$m_{Hgx} := \int_0^{\tau_x} \left[\alpha_{Hgx} \cdot e^{\beta_{Hgx} \cdot t} + \left(C_{goHgx} - \alpha_{Hgx} \right) \cdot e^{\gamma_x \cdot t} \right] \cdot Q_{ax} \, dt$$

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$$m_{Hgx} = 1.26 \times 10^{-2} \, kg$$

$t := 0hr, 1min.. 10min$ The results are plotted in Figure A.4.

$t =$		$C_{PCEx}(t) =$		$C_{TCEx}(t) =$		$C_{TCAx}(t) =$		$C_{Hgx}(t) =$	
0·100	min	1.56·101	ppm$_v$	3.15·101	ppm	4.86·100	ppm$_v$		mg/m³
1·100		1.23·101		2.49·101		3.82·100		1.77·102	
2·100		9.68·100		1.97·101		3.01·100		1.39·102	
3·100		7.64·100		1.56·101		2.37·100		1.1·102	
4·100		6.05·100		1.24·101		1.87·100		8.69·101	
5·100		4.81·100		9.93·100		1.48·100		6.89·101	
6·100		3.83·100		7.99·100		1.18·100		5.49·101	
7·100		3.07·100		6.47·100		9.43·10-1		4.39·101	
8·100		2.48·100		5.28·100		7.57·10-1		3.54·101	
9·100		2.02·100		4.36·100		6.12·10-1		2.87·101	
1·101		1.65·100		3.63·100		4.99·10-1		2.34·101	
								1.93·101	

Figure A.4
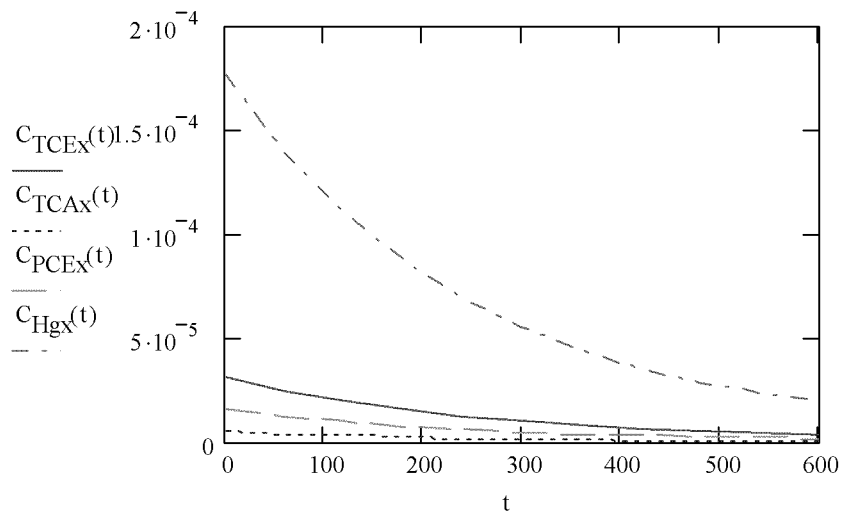
III.2.4.b V9 Results

The amount coming from V-9 is initially at equilibrium then falls off and becomes zero once all of the contents have been removed.

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PCE/V9 Results

Concentration vs. time:

$$C_{PCE9}(t) := \frac{R_{star}}{MW_{PCE}} \left[\alpha_{PCE9} e^{\beta_{PCE9} \cdot t} + \left(C_{goPCE9} - \alpha_{PCE9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot \Phi(\tau_9 - t)$$

$$C_{PCE9}(0hr) = 4.6 \times 10^3 \, ppm_v \qquad\qquad C_{PCE9}(\infty_i) = 0 \times 10^0$$

The time weighted average:

$$TWA_{PCE9} := \frac{R_{star}}{MW_{PCE} \Delta t} \cdot \int_0^{\tau_9} \left[\alpha_{PCE9} e^{\beta_{PCE9} \cdot t} + \left(C_{goPCE9} - \alpha_{PCE9} \right) \cdot e^{\gamma_9 \cdot t} \right] dt$$

$$TWA_{PCE9} = 1.47 \times 10^0 \, ppm_v$$

The total amount over the run time:

$$m_{PCE9} := \int_0^{\tau_9} \left[\alpha_{PCE9} e^{\beta_{PCE9} \cdot t} + \left(C_{goPCE9} - \alpha_{PCE9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot Q_{a9} \, dt$$

$$m_{PCE9} = 3.55 \times 10^{-2} \, kg$$

TCA/V9 Results

Concentration vs. time:

$$C_{TCA9}(t) := \frac{R_{star}}{MW_{TCA}} \cdot \left[\alpha_{TCA9} \cdot e^{\beta_{TCA9} \cdot t} + \left(C_{goTCA9} - \alpha_{TCA9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot \Phi(\tau_9 - t)$$

$$C_{TCA9}(0hr) = 1.78 \times 10^4 \, ppm_v \qquad\qquad C_{TCA9}(\infty_i) = 0 \times 10^0$$

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The time weighted average:

$$TWA_{TCA9} := \frac{R_{star}}{MW_{TCA} \cdot \Delta t} \cdot \int_0^{\tau_9} \left[\alpha_{TCA9} \cdot e^{\beta_{TCA9} \cdot t} + \left(C_{goTCA9} - \alpha_{TCA9} \right) \cdot e^{\gamma_9 \cdot t} \right] dt$$

$$TWA_{TCA9} = 5.39 \times 10^0 \, ppm_v$$

The total amount over the run time:

$$m_{TCA9} := \int_0^{\tau_9} \left[\left[\alpha_{TCA9} \cdot e^{\beta_{TCA9} \cdot t} + \left(C_{goTCA9} - \alpha_{TCA9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot Q_{a9} \right] dt$$

$$m_{TCA9} = 1.04 \times 10^{-1} \, kg$$

TCE/V9 Results

Concentration vs. time:

$$C_{TCE9}(t) := \frac{R_{star}}{MW_{TCE}} \cdot \left[\alpha_{TCE9} e^{\beta_{TCE9} \cdot t} + \left(C_{goTCE9} - \alpha_{TCE9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot \Phi\left(\tau_9 - t \right)$$

$$C_{TCE9}(0hr) = 3.78 \times 10^4 \, ppm_v \qquad\qquad C_{TCE9}\left(\infty_i \right) = 0 \times 10^0$$

The time weighted average:

$$TWA_{TCE9} := \frac{R_{star}}{MW_{TCE} \cdot \Delta t} \cdot \int_0^{\tau_9} \left[\alpha_{TCE9} e^{\beta_{TCE9} \cdot t} + \left(C_{goTCE9} - \alpha_{TCE9} \right) \cdot e^{\gamma_9 \cdot t} \right] dt$$

$$TWA_{TCE9} = 1.32 \times 10^1 \, ppm_v$$

The total amount over the run time:

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$$m_{TCE9} := \int_{0}^{\tau_9} \left[\alpha_{TCE9} e^{\beta_{TCE9} \cdot t} + \left(C_{goTCE9} - \alpha_{TCE9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot Q_{a9} \, dt$$

$$m_{TCE9} = 2.52 \times 10^{-1} \, kg$$

Hg/V9 Results

Concentration vs. time:

$$C_{Hg9}(t) := \left[\alpha_{Hg9} \cdot e^{\beta_{Hg9} \cdot t} + \left(C_{goHg9} - \alpha_{Hg9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot \Phi(\tau_9 - t)$$

$$C_{Hg9}(0hr) = 2.11 \times 10^2 \, \frac{mg}{m^3} \qquad\qquad C_{Hg9}(\infty_i) = 0 \times 10^0 \, \frac{mg}{m^3}$$

The time weighted average:

$$TWA_{Hg9} := \frac{1}{\Delta t} \cdot \int_{0}^{\tau_9} \left[\alpha_{Hg9} \cdot e^{\beta_{Hg9} \cdot t} + \left(C_{goHg9} - \alpha_{Hg9} \right) \cdot e^{\gamma_9 \cdot t} \right] dt$$

$$TWA_{Hg9} = 7.22 \times 10^{-2} \, \frac{mg}{m^3}$$

The total amount over the run time:

$$m_{Hg9} := \int_{0}^{\tau_9} \left[\alpha_{Hg9} \cdot e^{\beta_{Hg9} \cdot t} + \left(C_{goHg9} - \alpha_{Hg9} \right) \cdot e^{\gamma_9 \cdot t} \right] \cdot Q_{a9} \, dt$$

$$m_{Hg9} = 1.99 \times 10^{-4} \, kg$$

$t := 0hr, 1min .. 10min$ The results are plotted in Figure A.5.

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$t =$		$C_{PCE9}(t) =$		$C_{TCE9}(t) =$		$C_{TCA9}(t) =$		$C_{Hg9}(t) =$	
0·100	min	4.6·103	ppm_v	3.78·104	ppm_v	1.78·104	ppm_v	2.11·102	$\dfrac{mg}{m^3}$
1·100		1.83·101		1.94·102		5.84·101		1.37·100	
2·100		1.38·101		1.54·102		4.17·101		1.09·100	
3·100		1.29·101		1.44·102		3.91·101		9.96·10-1	
4·100		1.21·101		1.35·102		3.67·101		9.06·10-1	
5·100		1.13·101		1.26·102		3.44·101		8.24·10-1	
6·100		1.06·101		1.18·102		3.23·101		7.5·10-1	
7·100		9.97·100		1.11·102		3.03·101		6.82·10-1	
8·100		9.35·100		1.04·102		2.85·101		6.2·10-1	
9·100		8.77·100		9.72·101		2.67·101		5.64·10-1	
1·101		8.22·100		9.11·101		2.51·101		5.13·10-1	

Figure A.5

$C_{TCE9}(t)$
———
$C_{TCA9}(t)$
- - - -
$C_{PCE9}(t)$
·········
$C_{Hg9}(t)$
— · —
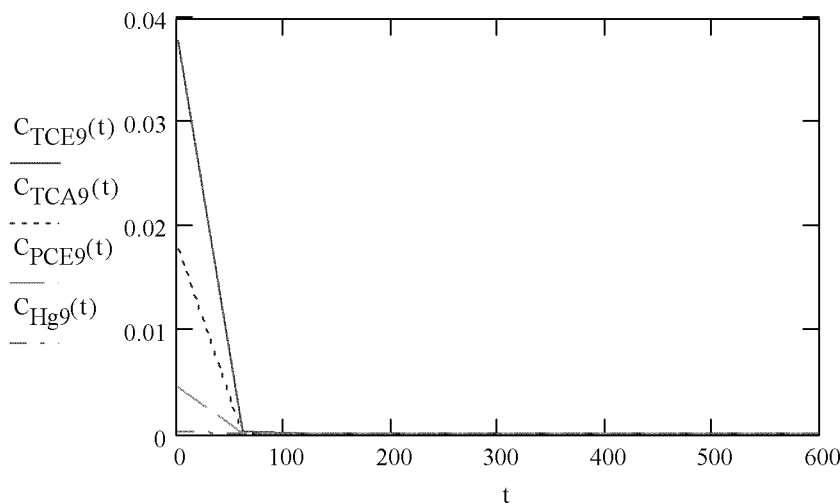
III.2.4.c Consolidation Tank Results

During fill and thereafter, assume equilibrium at the leakge rate.

PCE/C Results

$$C_{PCEc} := C_{PCE9}(0hr) \qquad\qquad C_{PCEc} = 4.6 \times 10^3 \ ppm_v$$

TCA/C Results

$$C_{TCAc} := C_{TCA9}(0hr) \qquad\qquad C_{TCAc} = 1.78 \times 10^4 \ ppm_v$$

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TCE/V9 Results

$$C_{TCEc} := C_{TCE9}(0hr) \qquad C_{TCEc} = 3.78 \times 10^4 \, ppm_v$$

Hg/V9 Results

$$C_{Hgc} := C_{Hg9}(0hr) \qquad C_{Hgc} = 2.11 \times 10^2 \, \frac{mg}{m^3}$$

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IV. Sparge the tanks to remove VOCs

Demonstrate that the 3 main VOCs can be removed in reasonable time. Also, determine the time to remove the worst-case VOC, i.e., 1,2 dichlorobenzene (H' = 0.07).

In Appendix B it is shown that the solids-liquid mass transfer coefficient is not rate limiting. Further research indicates that this is the case based on mixer correlations. Therefore, only the liquid-phase transfer coefficient is required. While a more conservative k_La was used in EDF-4602 Rev. 1, additional research has indicated that the correlations are consistent and predict fairly rapid removal.

The transient balance on 1,2-dcb for the solids:

$$\frac{d}{dt}X = -K_{oa\_La}\left(X - \frac{k_D \cdot p}{H}\right) \qquad \text{Since } k_S k_D \gg k_L a \qquad \text{(See Appendix B)}$$

$$K_{oa\_La} := k_{La}$$

Solve for p in terms of X:

$$\omega_s := \frac{Q_s}{R_{star}} \qquad\qquad \omega_s = 0.843 \frac{mol}{s}$$

At any point in time, the mass transfer rate is:

$$\omega = K_{oa\_La} \cdot M \cdot \left(X - \frac{k_D \cdot p}{H}\right)$$

$$\frac{p}{P} = \frac{\omega}{\omega + \omega_s} \qquad \text{Since } \omega \ll \omega_s \text{ (assumed, this assumption gets worse at lower flow):}$$

$$\frac{p}{P} = \frac{\omega}{\omega_s} = \frac{K_{oa\_La} \cdot M \cdot \left(X - \frac{k_D \cdot p}{H}\right)}{\omega_s}$$

$$p \cdot \left(\frac{1}{P} + \frac{K_{oa\_La} \cdot M \cdot k_D}{\omega_s \cdot H}\right) = \frac{K_{oa\_La} \cdot M \cdot X}{\omega_s}$$

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$$p \cdot \left(\frac{\omega_s \cdot H + K_{oa\_La} \cdot M \cdot k_D \cdot P}{P \cdot \omega_s \cdot H} \right) = \frac{K_{oa\_La} \cdot M \cdot X}{\omega_s}$$

$$p = \Lambda X \qquad \Lambda := \frac{P \cdot H_{dcb} \cdot k_{La\_dcb} \cdot M_{tk}}{\omega_s \cdot H_{dcb} + k_{La\_dcb} \cdot M_{tk} \cdot k_D \cdot P} \qquad \Lambda = 0.03 \frac{kg \cdot atm}{mol}$$

Now the derivative can be integrated

$$\int_{X_i}^{X_f} \frac{1}{X} \, dX = -k_{La} \cdot \left(1 - \Lambda \cdot \frac{k_D}{H} \right) t$$

For 99% removal

$$\ln\left(\frac{X_f}{X_i} \right) = -k_{La} \cdot \left(1 - \Lambda \cdot \frac{k_D}{H} \right) t \qquad t := \frac{\ln(0.01)}{-k_{La\_dcb} \cdot \left(1 - \frac{\Lambda \cdot k_D}{H_{dcb}} \right)} \qquad t = 168.04 hr$$

(For 1,2-DCB)

Also show as a function of time:

$$p = p_o \cdot e^{\left[-k_{La} \cdot \left(1 - \Lambda \cdot \frac{k_D}{H} \right) t \right]}$$

The above shows that DCB takes longer than the nominal target of 42 hours.

Based on sample extractions during recent sonication testing at MSE, the values for PCE, TCA, and TCA could be off by certain factors (Miller 2004). However, the 95% UCL values are used.

	X, mg/kg
PCE	1.46E+03
TCA	6.60E+02
TCE	4.62E+03
Hg	5.84E+02

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Check each of these individually to determine if they will be removed by 99% in the sludge phase. The target is 6 mg/kg based on total concentration. It is also desired to check the vapor concentration to determine range and accuracy of the VOC PID detector.

$$X_{PCE} := 1460\frac{mg}{kg} \qquad X_{TCA} := 660\frac{mg}{kg} \qquad X_{TCE} := 4620\frac{mg}{kg}$$

$$\Lambda_{PCE} := \frac{P \cdot H_{PCE} \cdot k_{La\_PCE} \cdot M_{tk}}{\omega_s \cdot H_{PCE} + k_{La\_PCE} \cdot M_{tk} \cdot k_D \cdot P} \qquad \Lambda_{PCE} = 0.26\frac{kg \cdot atm}{mol}$$

$$t_{PCE} := \frac{\ln(0.01)}{-k_{La\_PCE}\left(1 - \frac{\Lambda_{PCE} \cdot k_D}{H_{PCE}}\right)} \qquad t_{PCE} = 18.28\,hr$$

$$X_{PCE\_f} := 0.01 \cdot X_{PCE} \qquad X_{PCE\_f} = 14.6\frac{mg}{kg}$$

$$C_{TPCE} := \frac{X_{PCE\_f} \cdot M}{M + V_{liq} \cdot \rho_L} \qquad C_{TPCE} = 2.37 \times 10^0\frac{mg}{kg}$$

$$y_{PCE\_f} := \frac{\Lambda_{PCE} \cdot X_{PCE\_f}}{P \cdot MW_{PCE}} \qquad y_{PCE\_f} = 26.83\,ppm_v$$

$$\Lambda_{TCA} := \frac{P \cdot H_{TCA} \cdot k_{La\_TCA} \cdot M_{tk}}{\omega_s \cdot H_{TCA} + k_{La\_TCA} \cdot M_{tk} \cdot k_D \cdot P} \qquad \Lambda_{TCA} = 2.6 \times 10^{-1}\frac{kg \cdot atm}{mol}$$

$$t_{TCA} := \frac{\ln(0.01)}{-k_{La\_TCA}\left(1 - \frac{\Lambda_{TCA} \cdot k_D}{H_{TCA}}\right)} \qquad t_{TCA} = 1.83 \times 10^1\,hr$$

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$$X_{TCA\_f} := 0.01 \cdot X_{TCA}$$

$$X_{TCA\_f} = 6.6 \frac{mg}{kg}$$

$$C_{TTCA} := \frac{X_{TCA\_f} \cdot M}{M + V_{liq} \cdot \rho_L}$$

$$C_{TTCA} = 1.07 \times 10^0 \frac{mg}{kg}$$

$$y_{TCA\_f} := \frac{\Lambda_{TCA} \cdot X_{TCA\_f}}{P \cdot MW_{TCA}}$$

$$y_{TCA\_f} = 15.1 ppm_v$$

$$\Lambda_{TCE} := \frac{P \cdot H_{TCE} \cdot k_{La\_TCE} \cdot M_{tk}}{\omega_s \cdot H_{TCE} + k_{La\_TCE} \cdot M_{tk} \cdot k_D \cdot P}$$

$$\Lambda_{TCE} = 0.15 \frac{kg \cdot atm}{mol}$$

$$t_{TCE} := \frac{\ln(0.005)}{-k_{La\_TCE}\left(1 - \frac{\Lambda_{TCE} \cdot k_D}{H_{TCE}}\right)}$$

$$t_{TCE} = 3.54 \times 10^1 \, hr$$

Note: changed to 99.5%
to get $C_T < 6$ mg/kg

$$X_{TCE\_f} := 0.005 \, X_{TCE}$$

$$X_{TCE\_f} = 23.1 \frac{mg}{kg}$$

$$C_{TTCE} := \frac{X_{TCE\_f} \cdot M}{M + V_{liq} \cdot \rho_L}$$

$$C_{TTCE} = 3.74 \times 10^0 \frac{mg}{kg}$$

$$y_{TCE\_f} := \frac{\Lambda_{TCE} \cdot X_{TCE\_f}}{P \cdot MW_{TCE}}$$

$$y_{TCE\_f} = 31.85 ppm_v$$

For mercury

$$X_{Hg} := 584 \frac{mg}{kg}$$

$$X_{Hg\_m} := \frac{X_{Hg}}{MW_{Hg}}$$

$$\Lambda_{Hg} := \frac{P \cdot H_{Hg} \cdot k_{La\_Hg} \cdot M_{tk}}{\omega_s \cdot H_{Hg} + k_{La\_Hg} \cdot M_{tk} \cdot k_{D\_Hg} \cdot P}$$

$$\Lambda_{Hg} = 0.2 \frac{kg \cdot atm}{mol}$$

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$$t_{Hg} := \frac{\ln(0.01)}{-k_{La\_Hg} \cdot \left(1 - \frac{\Lambda_{Hg} \cdot k_{D\_Hg}}{H_{Hg}}\right)} \qquad\qquad t_{Hg} = 2.32 \times 10^{1}\, hr$$

Therefore, a reasonable time is obtained. There will be some that are not completely removed. However, the ones predicted to take longer are likely artifacts of characterization. A 42 hour number is used as it is near an average time to remove 99.9% of the main three VOCs.

Determine the average, 42 hour, average concentrations based on the 56.4 kg total and total concentrations in the liquid

$$t_s := 42\,hr \qquad\qquad M_{PCE} := 11\,kg$$

Using PCE again as an example:

$$y_{PCE\_s} := \frac{M_{PCE}}{Q_s \cdot t_s} \qquad\qquad y_{PCE\_s} = 3.85 \times 10^{0}\, \frac{mg}{L}$$

$$y_{PCE\_ppm} := \frac{y_{PCE\_s}}{MW_{PCE}} \cdot R_{star} \cdot 10^{6} \qquad\qquad y_{PCE\_ppm} = 5.2 \times 10^{2}$$

The rest are calculated similarly and put in a table (Table A.3) and in the body of the report under consolidation. Table A.3 is an average based on removing 56.4 kg of VOCs in 42 hours assuming all of the contaminates emit at the same, constant rate.

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Table A.3

	Consolidation		Sparging	
Flow, scfm	7	159	40	233
Temperature, °C	25	25	25	25
Humidity (RH)	100	100	100	100
VOCs, ppm$_v$	Raw	Dilute	Raw	Dilute
Benzene	0	0.00	0	0
bromomethane	91	3.85	18	3
Carbon disulfide	0	0.00	0	0
Chlorobenzene	0	0.00	0	0
Chloroethene (vinyl chloride)	65	2.75	86	15
chloromethane	11	0.46	19	3
1,2-dichlorobenzene	159	6.70	32	5
1,3-dichlorobenzene	212	8.93	41	7
1,4-dichlorobenzene	69	2.90	43	7
1,1-dichloroethane	67	2.82	14	2
cis-1,2-Dichloroethene	1	0.04	5	1
trans-1,2-dichloroethylene	15	0.64	24	4
1,1-Dichloroethene	2	0.09	5	1
Ethylbenzene	0	0.00	0	0
methylene chloride	44	1.87	77	13
4-Methyl-2-pentanone	0	0.00	0	0
Tetrachloroethylene (PCE)	165	6.94	518	89
Styrene	0	0.00	0	0
1,1,2,2-Tetrachloroethane	0	0.00	0	0
Toluene	0	0.02	6	1
1,2,4-Trichlorobenzene	48	2.04	33	6
1,1,2-Trichloroethane	0	0.01	0	0
1,1,1-Trichloroethane (TCA)	536	22.62	298	51
Trichloroethylene (TCE)	736	31.05	2081	358
xylene	0	0.00	2	0
Hg	3	0.15	2	0.37

Demonstrate that SVOCs are insignificant from sparging using Aroclor 1260 (Ar) as an example.

$$\Lambda_{Ar} := \frac{P \cdot H_{Aroclor1260} k_{La\_Ar} \cdot M_{tk}}{\omega_s \cdot H_{Aroclor1260} + k_{La\_Ar} \cdot M_{tk} \cdot k_{D\_Ar} \cdot P}$$

$$\Lambda_{Ar} = 1.11 \times 10^{-3} \frac{kg \cdot atm}{mol}$$

$$X_{Ar} := 144 \frac{mg}{kg \cdot MW_{Aroclor1260}}$$

$$p_{Ar} := \Lambda_{Ar} \cdot X_{Ar}$$

$$p_{Ar} = 4.91 \times 10^{-7} atm$$

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Hence, the SVOCs are insignificant

Calculate the initial concentrations and 42 hr-TWA for the main components PCE, TCA, TCE, and Hg:

$$p_{o\_PCE} := \frac{\Lambda_{PCE} X_{PCE}}{MW_{PCE}} \qquad\qquad p_{o\_PCE} = 2.28 \times 10^{-3} \, atm$$

$$p_{o\_TCA} := \frac{\Lambda_{TCA} \cdot X_{TCA}}{MW_{TCA}} \qquad\qquad p_{o\_TCA} = 1.28 \times 10^{-3} \, atm$$

$$p_{o\_TCE} := \frac{\Lambda_{TCE} X_{TCE}}{MW_{TCE}} \qquad\qquad p_{o\_TCE} = 5.42 \times 10^{-3} \, atm$$

The initial concentrations in ppm_V are:

$$C_{o\_PCE} := \frac{p_{o\_PCE}}{P} \qquad\qquad C_{o\_PCE} = 2.68 \times 10^3 \, ppm_V$$

$$C_{o\_TCA} := \frac{p_{o\_TCA}}{P} \qquad\qquad C_{o\_TCA} = 1.51 \times 10^3 \, ppm_V$$

$$C_{o\_TCE} := \frac{p_{o\_TCE}}{P} \qquad\qquad C_{o\_TCE} = 6.37 \times 10^3 \, ppm_V$$

Note: diluting from 40 scfm to 233 scfm and using the integral average (Chapra et al 1998)

$$mean = \frac{\int_a^b f(x) \, dx}{b - a} \qquad \Delta t_{42} := 42hr \qquad DF := 200 \qquad \Delta t_e := 42 \cdot hr$$

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$$\text{TWA\_PCE} := \frac{1}{\Delta t_{42}} \cdot \int_0^{\Delta t_{42}} C_{o\_PCE} \cdot e^{\left[-k_{La\_PCE}\left(1 - \frac{\Lambda_{PCE} \cdot k_D}{H_{PCE}} \right) \cdot t \right]} dt$$

$$\text{TWA\_PCE} = 253.57 \text{ppm}_v$$

$$\text{TWA\_TCA} := \frac{1}{\Delta t_{42}} \cdot \int_0^{\Delta t_{42}} C_{o\_TCA} \cdot e^{\left[-k_{La\_TCA}\left(1 - \frac{\Lambda_{TCA} \cdot k_D}{H_{TCA}} \right) \cdot t \right]} dt$$

$$\text{TWA\_TCA} = 1.43 \times 10^2 \text{ ppm}_v$$

The maximum concentration for mitigated TCA to compare to the IDLH:

$$\text{TWA\_TCE} := \frac{1}{\Delta t_{42}} \cdot \int_0^{\Delta t_{42}} C_{o\_TCE} \cdot e^{\left[-k_{La\_TCE}\left(1 - \frac{\Lambda_{TCE} \cdot k_D}{H_{TCE}} \right) \cdot t \right]} dt$$

$$\text{TWA\_TCE} = 1011.81 \text{ppm}_v$$

Mercury

$$k_{La\_Hg} = 4.6 \times 10^{-3} \frac{1}{s} \qquad\qquad \Lambda_{Hg} := \frac{P \cdot H_{Hg} \cdot k_{La\_Hg} \cdot M_{tk}}{\omega_s \cdot H_{Hg} + k_{La\_Hg} \cdot M_{tk} \cdot k_{D\_Hg} \cdot P}$$

$$\Lambda_{Hg} = 2.04 \times 10^{-1} \frac{kg \cdot atm}{mol}$$

$$p_{Hg} := X_{Hg\_m} \cdot \Lambda_{Hg} \qquad\qquad p_{Hg} = 5.96 \times 10^{-4} \text{ atm}$$

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$$C_{o\_Hg} := \frac{p_{Hg}}{R_g \cdot T_g} \cdot MW_{Hg} \qquad\qquad C_{o\_Hg} = 4.88 \times 10^3 \frac{mg}{m^3}$$

$$TWA\_Hg := \frac{1}{\Delta t_{42}} \cdot \int_0^{\Delta t_{42}} C_{o\_Hg} \cdot e^{\left[-k_{La\_Hg} \left(1 - \frac{\Lambda_{Hg} \cdot k_{D\_Hg}}{H_{Hg}} \right) \cdot t \right]} dt \qquad\qquad TWA\_Hg = 5.86 \times 10^2 \frac{mg}{m^3}$$

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V. GAC Design

A conservative design is to determine the worst-case isotherm (available) and design using the total mass (Army 2001). Of the 3 main VOCs, TCA is the worst-case isotherm based on having the lowest curves provided by the vendor (TIGG).

The data for TCA is vectorized from the TIGG data in Table A.4 and plotted in Figure A.1. The powerfit (standard Mathcad curve fit routine) values are plotted in Figure A.2:
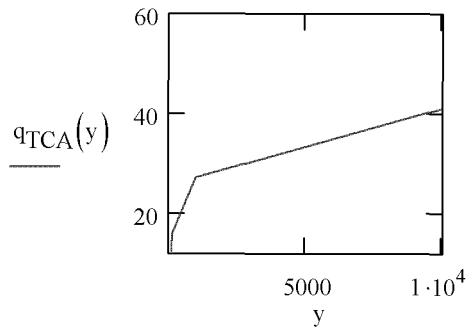
Table A.4

From TIGG @ 80%RH, 100°F	
ppmv	g/100g
0.1	2
1	4
10	7
100	16
1000	27
10000	41

$$q_{TCA}(y) := \begin{pmatrix} 2 \\ 4 \\ 7 \\ 16 \\ 27 \\ 41 \end{pmatrix} \qquad y := \begin{pmatrix} 0.1 \\ 1 \\ 10 \\ 100 \\ 1000 \\ 10000 \end{pmatrix}$$

y is ppm per Table A.4

Figure A.1

Assume Powerfit $\qquad f(x) = ax^b + c$

guessed vector for constants $\qquad\qquad$ Range $\qquad\qquad\qquad$ Domain

$$vg := \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \qquad vx := \begin{pmatrix} 0.1 \\ 1 \\ 10 \\ 100 \\ 1000 \\ 10000 \end{pmatrix} \qquad vy := \begin{pmatrix} 2 \\ 4 \\ 7 \\ 16 \\ 27 \\ 41 \end{pmatrix}$$

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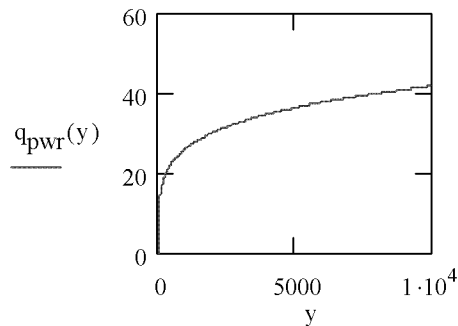**ENGINEERING DESIGN FILE**

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$$\text{pwrfit}(vx, vy, vg) = \begin{pmatrix} 9.03 \times 10^0 \\ 1.78 \times 10^{-1} \\ -4.87 \times 10^0 \end{pmatrix} \qquad q_{pwr}(y) := 9.03 y^{0.178} - 4.87$$

Set the range to plot the domain to

$y := 0, 10 .. 10000$

Figure A.2 shows the smoothed function

Figure A.2

$y_{TCA\_ppm} := 51$ (From Table A.3, average concentration for TCA)

$q_{pwr}(y_{TCA\_ppm}) = 1.33 \times 10^1$

The mass of **VOC** is 56.4 kg total.

$$M_{GAC\_est} := \frac{56.4 kg}{q_{pwr}(y_{TCA\_ppm})} \cdot 100 \qquad M_{GAC\_est} = 934.07 lb \qquad \text{about 20\%, a reasonable value}$$

From the vendor information, the sulfur is 13% do the fraction of carbon is:

$FrC := 0.87$

The amount of **S-GAC** needed by this conservative procedure is:

$$M_{SGAC} := \frac{M_{GAC\_est}}{FrC} \qquad M_{SGAC} = 1.07 \times 10^3 lb$$

Each TIGG unit has 400 lb of S-GAC so that the number of units is:

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$$N_{SGAC} := \frac{M_{SGAC}}{400 lb}$$

$$N_{SGAC} = 2.68$$

or 3 units. Since the operation is in parallel, it will be difficult to change out like that so the the order should be for 4 units.

The **S-GAC** at 13% is:

$$S_i := M_{SGAC} \cdot 0.13$$

$$S_i = 1.4 \times 10^2 \, lb$$

Easily accounting for the total Hg of 4 kg

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VI. Entrained Radionuclides and Loadings

To find the loadings for radionuclides, an entrainment function is needed. This was determined by plotting the upper curve of C' vs. DF in Figure 11-31 of Perry's 4th ed. This provides a particulate entrainment for evaporating liquid liquid, kg in vapor/kg liquid.

Where

$$C_{air} = \frac{G_{air}}{\sqrt{\rho_g \cdot (\rho_L - \rho_g)}}$$

$$G_{air} := \frac{Q_s \cdot \rho_g}{A_{tk}}$$

$$G_{air} = 1.93 \frac{lb}{ft^2 \cdot hr}$$

$$C_{air} := \frac{G_{air}}{\sqrt{\rho_g \cdot (\rho_L - \rho_g)}}$$

$$C_{air} = 9.712 \times 10^{-1} \frac{ft}{hr}$$

$$E_p := 2650.4 \left(\frac{C_{air}}{UnitsOf(C_{air})} \right)^{-.3062}$$

$$E_p = 4.722 \times 10^4 \frac{kg}{kg}$$

kg of vapor per kg of entrained liquid

Applying this to the radionuclides using Sr as an example (using total concentration as an example):

$$C_{Sr} := 1.21 \cdot 10^3 \frac{nCi}{mL}$$

$$y_{Sr} := \frac{C_{Sr} \cdot \rho_g}{E_p \cdot \rho_{H2O}}$$

$$y_{Sr} = 2.586 \times 10^{-11} \frac{Ci}{L}$$

(A gas phase liquid concentration based on liquid/solid concentration)

Compare this to plotting the data provided by Othmer (Othmer et al 2004).

$$v := \frac{Q_s}{\frac{\pi}{4} \cdot D_{tk}^2}$$

$$v = 8.49 \times 10^{-3} \frac{ft}{s}$$

$$E_o := 2.752 \left(\frac{v}{UnitsOf(v)} \right)^{-1.9577}$$

$$E_o = 3.2 \times 10^5 \frac{kg}{kg}$$

kg of vapor per kg of entrained liquid

The gas phase concentration is then:

$$y_{Sr} := \frac{C_{Sr} \cdot \rho_g}{E_o \cdot \rho_{H2O}}$$

$$y_{Sr} = 3.82 \times 10^{-12} \frac{Ci}{L}$$

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Use the Perry's data since it is higher.

The emission rate equals the deposition rate assuming no DF for upstream equipment:

$$r_{Sr} := y_{Sr} \cdot Q_s \qquad\qquad r_{Sr} = 2.6 \times 10^{-7} \frac{Ci}{hr}$$

$$L_{Sr} := \frac{r_{Sr} \cdot t_s \cdot 2}{M_{SGAC}} \qquad\qquad L_{Sr} = 4.479 \times 10^{-8} \frac{Ci}{kg} \qquad\qquad \rho_g = 1.01 \times 10^{-3} \frac{kg}{L}$$

Assuming that there is a DF of 50 from the scrubber and 100 for the HEPA:

$$DF_s := 50 \qquad\qquad DF_H := 100$$

$$L_{Sr2} := \frac{L_{Sr}}{DF_s \cdot DF_H} \qquad\qquad L_{Sr2} = 8.96 \times 10^{-12} \frac{Ci}{kg}$$

An Excel spreadsheet was determined for these including accumulation charts based on (e.g. scrubber):

$$C(liquid) = \frac{Q_s}{V_{scrubber}} \cdot \left(C_{in} - \frac{C_{in}}{DF} \right) \cdot t$$

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VII. Site Worker Protection

Mercury was previously targeted for removal. Since the APAD did not identify any problem with mercury, it's based on local worker protection.

Calculate the time weighted average (TWA)-threshold limit vale (TLV) for PCE, TCA, and TCE based on the C vs. t relation:

$$P_{o\_PCE} := \frac{\Lambda_{PCE} X_{PCE}}{MW_{PCE}} \qquad\qquad P_{o\_PCE} = 2.28 \times 10^{-3} \text{ atm}$$

$$P_{o\_TCA} := \frac{\Lambda_{TCA} \cdot X_{TCA}}{MW_{TCA}} \qquad\qquad P_{o\_TCA} = 1.28 \times 10^{-3} \text{ atm}$$

$$P_{o\_TCE} := \frac{\Lambda_{TCE} X_{TCE}}{MW_{TCE}} \qquad\qquad P_{o\_TCE} = 5.42 \times 10^{-3} \text{ atm}$$

$$Q_s := 40 \frac{ft^3}{min} \qquad\qquad Q_T := 230 \frac{ft^3}{min}$$

The initial concentrations in ppm_V are:

$$C_{o\_PCE} := \frac{P_{o\_PCE}}{P} \cdot \frac{Q_s}{Q_T} \qquad\qquad C_{o\_TCA} := \frac{P_{o\_TCA}}{P} \cdot \frac{Q_s}{Q_T}$$

$$C_{o\_TCE} := \frac{P_{o\_TCE}}{P} \cdot \frac{Q_s}{Q_T}$$

Note: diluting from 40 scfm to 230 scfm and using the integral average (Chapra et al 1998)

$$mean = \frac{\int_a^b f(x)\, dx}{b - a} \qquad\qquad \Delta t := 10 hr \qquad\qquad DF := 200 \qquad\qquad \Delta t_e := 42 \cdot hr$$

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$$\text{TWA\_PCE} := \frac{1}{\text{DF} \cdot \Delta t} \cdot \int_0^{10\text{hr}} C_{o\_\text{PCE}} \cdot e^{\left[-k_{\text{La\_PCE}} \left(1 - \frac{\Lambda_{\text{PCE}} \cdot k_D}{H_{\text{PCE}}} \right) \cdot t \right]} dt$$

$$\text{TWA\_PCE} = 0.85 \text{ppm}_v \qquad\qquad \text{Less than the TLV of 25 TWA}$$

The maximum concentration for mitigated PCE to compare to the **IDLH**:

$$C_{o\_\text{PCE\_max}} := \frac{C_{o\_\text{PCE}}}{\text{DF}} \qquad\qquad C_{o\_\text{PCE\_max}} = 2.33 \times 10^0 \text{ppm}_v$$

The emission rate for **PCE** is:

The emission rate is:

$$\Omega_{\text{PCE}} := \frac{\text{MW}_{\text{PCE}}}{\text{DF} \cdot \Delta t_e \cdot R_{\text{star}}} \cdot \int_0^{42\text{hr}} C_{o\_\text{PCE}} \cdot Q_T \cdot e^{\left[-k_{\text{La\_PCE}} \left(1 - \frac{\Lambda_{\text{PCE}} \cdot k_D}{H_{\text{PCE}}} \right) \cdot t \right]} dt$$

$$\Omega_{\text{PCE}} = 1.41 \times 10^{-3} \frac{\text{lb}}{\text{hr}}$$

$$\text{TWA\_TCA} := \frac{1}{\text{DF} \cdot \Delta t} \cdot \int_0^{10\text{hr}} C_{o\_\text{TCA}} \cdot e^{\left[-k_{\text{La\_TCA}} \left(1 - \frac{\Lambda_{\text{TCA}} \cdot k_D}{H_{\text{TCA}}} \right) \cdot t \right]} dt$$

$$\text{TWA\_TCA} = 4.79 \times 10^{-1} \text{ppm}_v \qquad\qquad \text{Less than the TLV of 10 TWA}$$

The maximum concentration for mitigated TCA to compare to the **IDLH**:

$$C_{o\_\text{TCA\_max}} := \frac{C_{o\_\text{TCA}}}{\text{DF}} \qquad\qquad C_{o\_\text{TCA\_max}} = 1.31 \times 10^0 \text{ppm}_v$$

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The emission rate for TCA is:

The emission rate is:

$$\Omega_{TCA} := \frac{MW_{TCA}}{DF \cdot \Delta t_e \cdot R_{star}} \cdot \int_0^{42hr} C_{o\_TCA} \cdot Q_T \cdot e^{\left[-k_{La\_TCA} \left(1 - \frac{\Lambda_{TCA} \cdot k_D}{H_{TCA}} \right) \cdot t \right]} dt$$

$$\Omega_{TCA} = 6.36 \times 10^{-4} \frac{lb}{hr}$$

$$TWA\_TCE := \frac{1}{DF \cdot \Delta t} \cdot \int_0^{10hr} C_{o\_TCE} \cdot e^{\left[-k_{La\_TCE} \left(1 - \frac{\Lambda_{TCE} \cdot k_D}{H_{TCE}} \right) \cdot t \right]} dt$$

$$TWA\_TCE = 0 \hspace{3cm} \text{Less than the TLV of 25 TWA}$$

The maximum concentration for mitigated TCE to compare to the IDLH:

$$C_{o\_TCE\_max} := \frac{C_{o\_TCE}}{DF} \hspace{2cm} C_{o\_TCE\_max} = 5.54 \times 10^0 \, ppm_v$$

The emission rate for TCE is:

The emission rate is:

$$\Omega_{TCE} := \frac{MW_{TCE}}{DF \cdot \Delta t_e \cdot R_{star}} \cdot \int_0^{42hr} C_{o\_TCE} \cdot Q_T \cdot e^{\left[-k_{La\_TCE} \left(1 - \frac{\Lambda_{TCE} \cdot k_D}{H_{TCE}} \right) \cdot t \right]} dt$$

$$\Omega_{TCE} = 4.45 \times 10^{-3} \frac{lb}{hr}$$

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Mercury

$$k_{La\_Hg} = 4.6 \times 10^{-3} \frac{1}{s} \qquad \Lambda_{Hg} := \frac{P \cdot H_{Hg} \cdot k_{La\_Hg} \cdot M_{tk}}{\omega_s \cdot H_{Hg} + k_{La\_Hg} \cdot M_{tk} \cdot k_{D\_Hg} \cdot P}$$

$$\Lambda_{Hg} = 2.04 \times 10^{-1} \frac{kg \cdot atm}{mol}$$

$$p_{Hg} := X_{Hg\_m} \cdot \Lambda_{Hg} \qquad\qquad p_{Hg} = 5.96 \times 10^{-4} \ atm$$

$$C_{o\_Hg} := \frac{p_{Hg}}{R_g \cdot T_g} \cdot MW_{Hg} \cdot \frac{Q_s}{Q_T} \qquad\qquad C_{o\_Hg} = 8.49 \times 10^2 \frac{mg}{m^3}$$

$$TWA\_Hg := \frac{1}{\Delta t \cdot DF} \cdot \int_0^{10hr} C_{o\_Hg} \cdot e^{\left[-k_{La\_Hg}\left(1 - \frac{\Lambda_{Hg} \cdot k_{D\_Hg}}{H_{Hg}}\right) \cdot t \right]} dt \qquad TWA\_Hg = 1.85 \times 10^0 \frac{mg}{m^3}$$

The maximum concentration for mitigated Hg to compare to the IDLH:

$$C_{o\_Hg\_max} := \frac{C_{o\_Hg}}{DF} \qquad\qquad C_{o\_Hg\_max} = 4.24 \times 10^0 \frac{mg}{m^3}$$

The emission rate for Hg is:

The emission rate is:

$$\Omega_{Hg} := \frac{1}{DF \cdot \Delta t_e} \cdot \int_0^{42 \cdot hr} C_{o\_Hg} \cdot Q_T \cdot e^{\left[-k_{La\_Hg}\left(1 - \frac{\Lambda_{Hg} \cdot k_{D\_Hg}}{H_{Hg}}\right) \cdot t \right]} dt$$

$$\Omega_{Hg} = 4.39 \times 10^{-4} \frac{lb}{hr}$$

This exceeds the 10-hr TWA of 0.01 mg/m^3 for elemental and 0.03 mg/m^3 for allyl-Hg so check dispersion from a 20 ft stack.

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See Figure A.7 for coordinates (the nomenclature of Parnell et al is used).Since the origin is set at the stack centerline, x_{source} and y_{source} are zero. Also, the y is at midplane and also zero.

The concentration at point (x,y,z) is (Parnell et al 2003):

$$C(x,y,z) = \frac{E}{2 \cdot \pi \cdot u \cdot \sigma_y \cdot \sigma_z} \cdot e^{\frac{-1}{2} \cdot \frac{y^2}{\sigma_y^2}} \cdot \left[e^{\left[\frac{-1}{2} \cdot \frac{(z-H)^2}{\sigma_z^2} \right]} + e^{\left[\frac{-1}{2} \cdot \frac{(z+H)^2}{\sigma_z^2} \right]} \right]$$

$$E := C_{o\_Hg\_max} \cdot Q_T \qquad\qquad u := 15 \frac{mi}{hr}$$

$$z := 6ft \qquad\qquad H_s := 12ft \qquad\qquad y := 0ft \qquad\qquad \theta := 45deg$$

Note, z is the height of an individual

$$x_{rec} := 10ft \qquad\qquad x_{source} := 0ft \qquad\qquad y_{rec} := 10ft \qquad\qquad y_{source} := 0ft$$

$$X := \left(x_{rec} - x_{source} \right) \cdot \sin(\theta) + \left(y_{rec} - y_{source} \right) \cdot \cos(\theta) \qquad\qquad X = 4.31 \times 10^0 m$$

Figure A.7
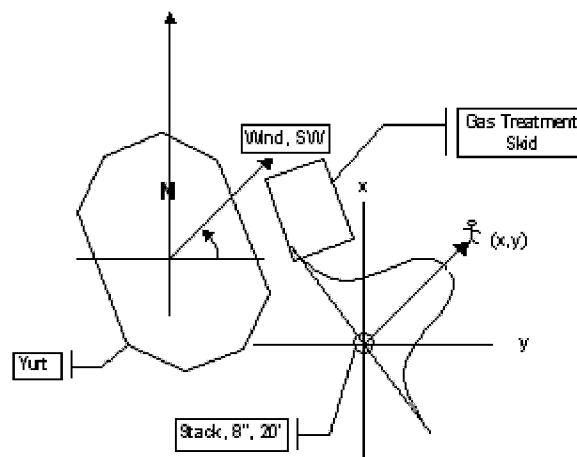
Worst-case is Class F. For less than 0.2 km,

$$a := 15.209r \qquad\qquad b := 0.8155 \qquad\qquad c := 4.1667deg \qquad\qquad d := 0.36191deg$$

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$$T_i := c - d \cdot \ln\left(\frac{X}{UnitsOf(X)}\right) \qquad\qquad T_i = 3.64 \times 10^0 \, deg$$

$$\sigma_y := \frac{X \cdot \tan(T_i)}{2.15} \qquad\qquad \sigma_z := a \cdot \left(\frac{X}{UnitsOf(X)}\right)^b$$

$$\sigma_y = 1.27 \times 10^{-1} \, m \qquad\qquad \sigma_z = 5.01 \times 10^1 \, m$$

$$C_{Hg} := \frac{E}{2 \cdot \pi \cdot u \cdot \sigma_y \cdot \sigma_z} \cdot \left[e^{\left[\frac{-1}{2} \cdot \frac{y^2}{\sigma_y^2}\right]} \cdot \left[e^{\left[\frac{-1}{2} \cdot \frac{(z-H_s)^2}{\sigma_z^2}\right]} + e^{\left[\frac{-1}{2} \cdot \frac{(z+H_s)^2}{\sigma_z^2}\right]} \right] \right]$$

$$C_{Hg} = 0.00342 \frac{mg}{m^3}$$

Thus meeting the TWA-TLV for elemental and allyl-Hg at the worst-case position of (10 ft, 10 ft, and 6 ft tall individual) in-line with the prevailing SW winds.

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VIII. System Safety

Examine the kinetics of carbon and sulfur reacting with oxygen. Thermodynamics indicates that the reaction is spontaneous in our temperature range, T = 30 - 120°F. The process depends on the mass transfer coupled with chemical kinetics that are well known for C/O_2 (Levenspiel 1972). For sulfur, Calgon Carbon indicated that there should be no problem based on their experience (Ashworth 2004c). Therefore, the focus is on carbon.

$$\frac{-1}{A_{surf}} \cdot \left(\frac{d}{dt} N_{GAC} \right) = k_{oa} \cdot C_{O2} \qquad\qquad k_{oa} = \frac{1}{\dfrac{1}{k_s} + \dfrac{1}{k_g}}$$

A_{surf} is approximately 1000 m^2/g, the surface area of GAC

The reaction kinetics are known (Levenspiel 1972):

$$k_s = \frac{4.32 \, 10^{11}}{\sqrt{T}} \cdot e^{\frac{-44000cal}{RT}} \qquad\qquad k_s \text{ in cm/s}$$

k_g is found from the Sherwood number:

$$Sh = 2 + 0.6 \, Sc^{\frac{1}{3}} \cdot Re^{\frac{1}{2}}$$

To obtain a rough estimate, assume the carbon particles are small enough that Sh = 2 and that diffusivity stays constant at:
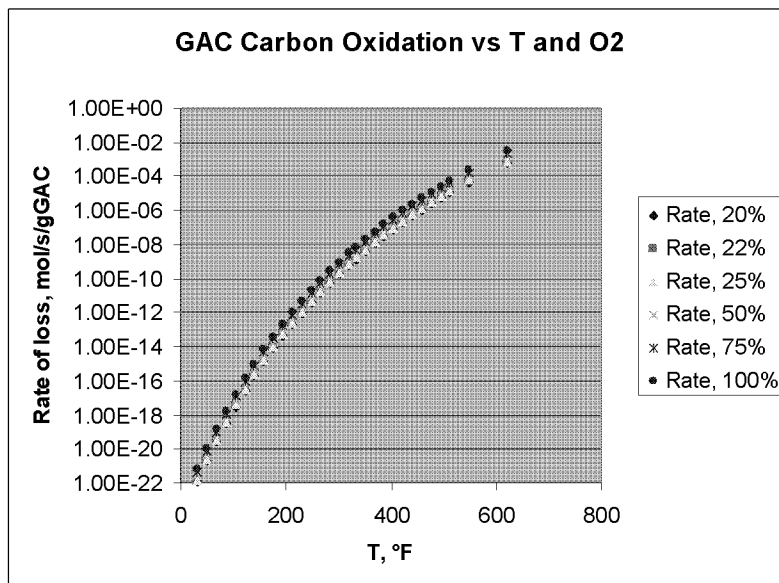
$$D_{O2} := 0.2 \frac{cm^2}{s} \qquad\qquad \text{(Thibodeaux 1979)}$$

The GAC particles are 4 x 10 U.S. sieve, a cylinder 4.76 mm x 1.68 mm, use:

$$d_{GAC} := 4.76 mm$$

$$k_g := \frac{2 \cdot D_{O2}}{d_{GAC}} \qquad\qquad k_g = 8.4 \times 10^{-1} \frac{cm}{s} \qquad\qquad k_{oa} = \frac{1}{\dfrac{1}{\dfrac{4.32 \, 10^{11}}{\sqrt{T}} \cdot e^{\frac{-44000cal}{R_g \cdot T}}} + \dfrac{1}{k_g}}$$

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The rate was plotted at several oxygen concentrations using T as the independent variable. The results are shown in Figure A.8. The oxidation rates are very small for all oxygen concentrations at the temperature ranges expected (up to 120°F).

Figure A.8

GAC Carbon Oxidation vs T and O2

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Nomenclature

a,b,c,d	Constants, various
a/δ	Ratio from hole theory of liquids
A	Area
C	Concentration
C_{air}	Virtual air velocity
C_g	Gas concentration
C_L	Liquid concentration
D	Diameter
df	Degrees of Freedom
DF	Decontamination factor
D_{imp}	Impeller diameter
D_{tk}	Tank diameter
E	Entrainment, emission rate
F_d	Displacement liquid flow
fi	Error factors for VOCs
f_{oc}	Fraction organic carbon
f_{safety}	Safety factor, mass transfer
g_c	Gravity conversion
g	Gravity acceleration
G	Mass velocity
h	Height, Plank's constant
H	Henry's constant, stack height
H'	Dimensionless Henry's constant
J	Dimensionless concentration
k_D	Solid-liquid partition coefficient
K	Mass transfer coefficient
K_D	Gas-GAC partition coefficient
k_g	Gas phase transfer coefficient
k_H	Inverse Henry's (i.e. solubility)
$k_L a$	Liquid phase mass transfer coefficient
k_s	Solid reaction rate coefficient
$K_{oaL}a$	Overall mass transfer coefficient
K_{oc}	Organic carbon partition coefficient
K_{ow}	Octanol-water partition coefficient
L	Loading
m	Moles

M	Mass
MW	Molecular Weight
n	Number of something
N	Impeller speed
N_{AV}	Avogadro's Number
p_i	Partial pressure of i
P	Pressure
P_{ow}	Power
q	Isotherm, mL/g
Q	Flow rate, Dimensionless q
Q_d	Displacement gas flow
Q_L	Gas leak flow
Q_s	Sparge gas flow
Q_T	Total gas flow
Q_v	V-Tank Vent flow
r	Rate
R	Retardation factor, gas constant
R^2	Correlation coefficient
Re	Reynolds number
R_g	Gas constant
R_{star}	Volume per mole
Sc	Schmidt number
Sh	Sherwood number
t	Time
T	Temperature, 1/2 Pasquill Θ
T_b	Boiling temperature
TINV()	EXCEL worksheet function
u	Wind velocity
v	Velocity
v_R	Retarded velocity
vg	Guess vector
vx	x data vector
vy	y data vector
V	Volume, molar volume
Vg	Gas volume
VL	Liquid volume
Vm	Molar volume
y_i	ppm or Mole fraction of i, gas

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Greek

α,β,γ	Constants
α	v/R
δ/a	Spacing factor, liquid
ΔG_0	Free Energy of Activation
ΔP	Pressure drop
ε_s	Efficiency
Θ	Wind angle
Λ	Stripping factor
μ	Viscosity
ρ	Density
σ_y	Horizontal dispersion
σ_z	Vertical dispersion
τ	Residence time
Ξ	Gassed power number
Φ	Heavyside step function
Ψ	Probability, transformed variable
ω	Mole rate, mass transfer
Ω	Emission rate

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Appendix B

Air Stripping of VOCs from Slurries in a Batch Air-Sparged, Agitated Tank

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Appendix B

Air Stripping of VOCs from Slurries in a Batch Air-Sparged, Agitated Tank

B-1. BACKGROUND

Chlorides represent a potential materials corrosion problem for treating V-Tank wastes. If chlorinated VOCs are stripped out prior to any treatment (for PCB, BHP, etc.), the residual chloride level is reduced to 100-200 mg/L. This document attempts to explain some of the complicating factors associated with stripping, provide justification for testing methodology, and to provide initial estimates for laboratory conditions. Further, it discusses the methods of obtaining required mass transfer coefficients for scale-up to apply to the full-scale system.

B-2. INTRODUCTION

Figure B-1 shows a transfer from mole fraction x_A in the bulk liquid to an interface at x_{Ai}. Figure B-2 illustrates the driving force concepts. This is called the liquid phase transfer and is designated as:

$$N_{AL} = k_L^{'}(x_A - x_{Ai})$$ (1)

At the interface, the liquid and gas are in equilibrium such that:

$$y_{Ai} = H^{'}x_{Ai}$$ (2)

The transfer continues as long is there is a driving force[r] from y_{Ai} to y_A. If the rates are low[s] (Thibodeaux 1979), then the gas transfer is designated as:

$$N_{AG} = k_G^{'}(y_{Ai} - y_A)$$ (3)

These two rates are equal and designated N_A. There are two overall relations that can be used interchangeably depending on the ease of use. These are based on virtual or non-existent liquid concentration in the vapor ($x_A^* = y_A/H$) and vapor concentration in the liquid ($y_A^* = x_A H$)[t]:

$$N_A = K_L^{'}(x_A - x_A^*)$$ (4)

$$N_A = K_G^{'}(y_A^* - y_A)$$ (5)

Adding the differences, $K_L^{'}$ is found, hence:

---

[r]. If there is no driving force, the curves are flat and the gas is in equilibrium with the liquid.

[s]. Otherwise, the mass transfer coefficient may be a function of the mass transfer rate.

[t]. Note that although these are virtual, they are used extensively in mass transfer.

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$$\frac{N_A}{K_L^{'}} = \left(x_A - x_{Ai}\right) + \left(x_{Ai} - x_A^{*}\right)$$

(6)

Since $y_{Ai} = H^{'}x_{Ai}$ and $y_A = H^{'}x_A^{*}$ and canceling the N_A's:

$$\frac{1}{K_L^{'}} = \frac{1}{k_L^{'}} + \frac{1}{H^{'}k_G^{'}}$$

(7)

A similar derivation can be done for the gas phase with the result being:
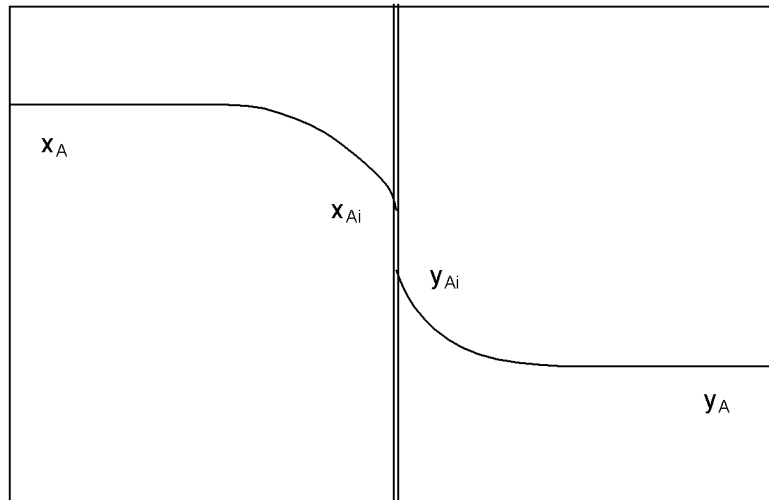
$$\frac{1}{K_G^{'}} = \frac{1}{k_G^{'}} + \frac{H^{'}}{k_L^{'}}$$

(8)

Figure B-1. Interphase Mass Transfer, Stripping.

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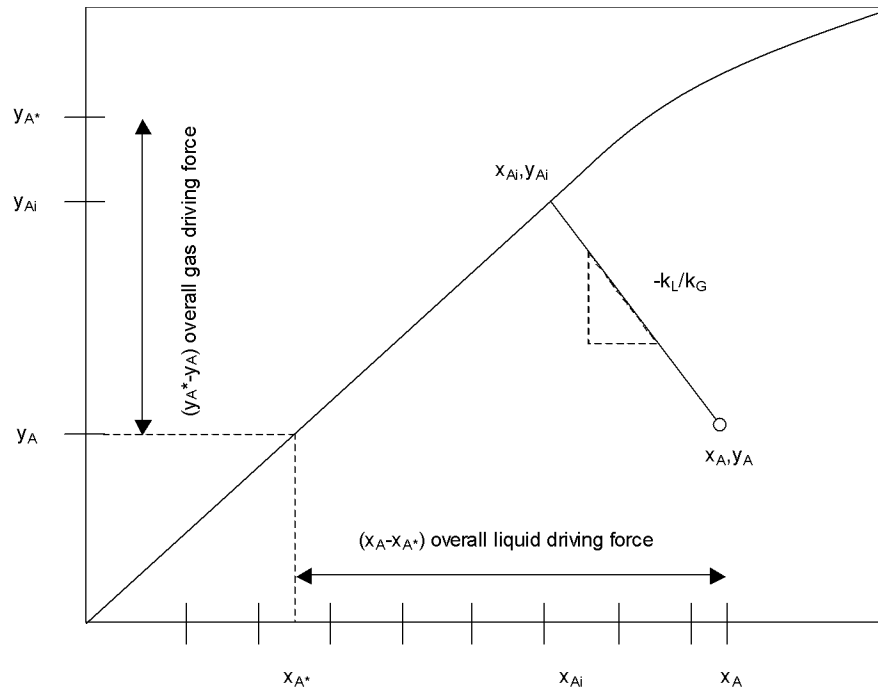
Figure B-2. Interphase Driving Forces.

An analogue can be found using concentrations with appropriate Henry's Law constants and mass transfer coefficients, i.e.:

$$N_A = K_L(C_A - C_A^*) \tag{9}$$

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{Hk_G} \tag{10}$$

For VOC's, the liquid phase is normally controlling[u]. Further, the areas needed for an actual molar flow rate are difficult to determine and are usually lumped together.

$$K_L \cong k_L \tag{11}$$

$$k_L A = k_L a V \tag{12}$$

Where the "a" is the specific area of bubbles per volume of batch tank.

An analogous method is performed for the solid to liquid transfer as shown in Figure B-3.

$$N_{AS} = k_S \left(X_A - X_{Ai} \right) \tag{13}$$

$$N_{AL} = k_L \left(C_{Ai}^s - C_{Ai}^L \right) \tag{14}$$

---

[u]. Note, some use K_L and k_L interchangeably.

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$$N_{AG} = k_G (p_i - p) \tag{15}$$

$$N_A = K_{oaS} (X_A - X_A^{**}) \tag{16}$$

$$N_A = K_{oaL} (C_A^{**} - C_A^{*}) \tag{17}$$

Where $C_A^{**} = X_A/k_D$, with k_D being the distribution coefficient. A relation is needed for the **'s. The X_A^{**} needs to be is mol/kg or mg/kg so that:

$$X_A^{**} = \frac{p_A k_D}{H} \tag{18}$$

Likewise with C_A^{*}:

$$C_A^{*} = \frac{p_A}{H} \tag{19}$$

The method of finding the overall coefficient based by necessity on the liquid coefficient is:

$$\frac{N_A}{K_{oaL}} = \left(C_A^{**} - C_{Ai}^{S}\right) + \left(C_{Ai}^{S} - C_{Ai}^{L}\right) + \left(C_{Ai}^{L} - C_A^{*}\right) \tag{20}$$

$$\frac{N_A}{K_{oaL}} = \frac{1}{k_D}(X_A - X_{Ai}) + \frac{N_A}{k_L} + \frac{1}{H}(p_i - p) \tag{21}$$

$$\frac{1}{K_{oaL}} = \frac{1}{k_D k_S} + \frac{1}{k_L} + \frac{1}{H k_G} \tag{22}$$

As discussed previously, there is a need for areas to obtain molar or mass rates:

$$\frac{1}{K_{oaL} a_{oa}} = \frac{1}{k_D k_S a'} + \frac{1}{k_L a} + \frac{1}{H k_G a} \tag{23}$$

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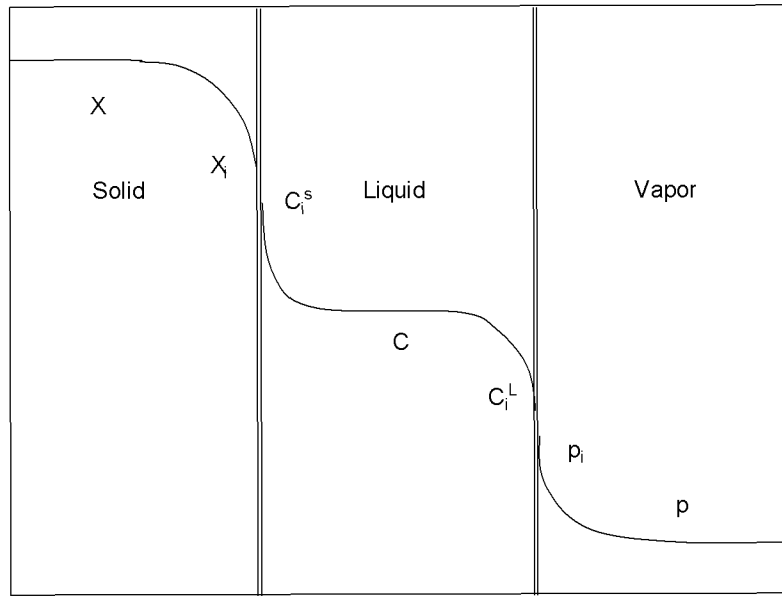
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Figure B-3. Overall Transfer.

B-3. ESTIMATING RATES FROM CORRELATIONS

Solids-Free Water. For solids-free water and liquid rate limiting, the following is found:

$$\frac{dC}{dt} = k_L a \left(C - C^* \right) \tag{24}$$

Since both quantities vary, need a relation between C and C^*. The instantaneous mass transfer is:

$$\omega = k_L aV \left(C - C^* \right) \tag{25}$$

Since the pressure fraction = volume fraction:

$$\frac{p}{P} = \frac{\omega}{\omega + \omega_{air}} \tag{26}$$

$$\frac{p}{P} = \frac{k_L aV \left(C - C^* \right)}{\omega + \omega_{air}} \tag{27}$$

If it is assumed that $\omega \ll \omega_{air}$, then (27) becomes:

$$\frac{p}{P} = \frac{k_L aV \left(C - p/H \right)}{\omega_{air}} \tag{28}$$

$$p = \frac{k_L aVPHC}{H\omega_{air} + k_L aVP} \cong \frac{k_L aVPC}{\omega_{air}} \tag{29}$$

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The above (29) indicates that p is small and p/H (C^*) is smaller and can be neglected in (24) for some cases.

If the assumption in (28) cannot be made:

$$p = \frac{-b - \sqrt{b^2 - 4\chi C}}{2\chi} \tag{30}$$

Where $\quad b = -\left(\frac{1}{H} + \frac{C}{P} + \frac{\omega_{air}}{k_L a V P}\right), \quad \chi = \frac{1}{HP}$

The mass transfer coefficient is dependent on the physics of the system and not the concentration or the mass transfer rate at low rates. The general correlation has been found to be:

$$k_L a = \alpha \left(\frac{P'}{V_L}\right)^\beta v_G^\gamma \tag{31}$$

The constants α, β, and γ in (31) vary depending on the reference but based on several references (Perry & Green, 1984, Harnby et al 1992), it is recommended that: "α" be found by experiment, β and γ from Harby or Perry's. Without any experimental data, it is recommended that "α" take one of the values for non-ionic liquids for this particular case.

Several other correlations were found that indicate the kLa from Perry's is applicable, that is if testing on the actual waste cannot be done. The literature includes:

Van't Riet (Van't Riet 1979) that appears to be the original data quoted by Perry's

Yagi et al 1975

Valentin 1967

Höcker et al 1981

Zlokarnik 1978

Using the calculated $k_L a$, the time is found by integrating (24):

$$t = \frac{-1}{k_L a} \ln\left(\frac{C_f}{C_i}\right) \tag{32}$$

Solids-Containing Water. For the case of solids containing VOCs in addition to the liquid, the overall coefficient needs to be used in terms of the liquid:

$$\frac{dC^{**}}{dt} = K_{oaL} a_{oa} (C^{**} - C^*) \tag{33}$$

$$\frac{dX/k_D}{dt} = K_{oaL} a_{oa} (X/k_D - \frac{p}{H}) \tag{34}$$

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$$\frac{dX}{dt} = K_{oaL}a_{oa}(X - \frac{k_D p}{H}) \tag{35}$$

Where $\qquad K_{oaL}a_{oa} = \dfrac{1}{\dfrac{1}{k_D k_S a'} + \dfrac{1}{k_L a}}$

From Chrysikopoulos et al 2003 it is found that K_p levels out at about 0.06 cm/h shown in B-4 (the liquid velocity from mixing in an air-sparge, agitated system past a particle is expected to exceed this). However, it's not an equivalent analogue. Braida (Braida and Ong, 2000) correlated the k_S with the Sherwood number for air flowing through porous particles that may be a better analogue:

$$Sh = \frac{k_S a' d_p^2}{D} \tag{36}$$

The Sherwood number for like-kind systems is (see Oldshue 1983, Harnby 1992) :

$$Sh = 2 + 0.72 \, \mathrm{Re}_p^{1/2} \, Sc^{1/3} \tag{37}$$

This becomes 2 as dp $\to\infty$ so (37) can be set to 2 and obtain:

$$k_S = \frac{2D}{a' d_p^2} \tag{38}$$

The specific surface area (a') can be calculated based on the mmpd, 144 mμ.

$$a' = \frac{3(1-n)}{2D_p \rho_s} = \frac{3*0.5}{2*144x10^{-6} \rho_s} = \frac{5200 \, m^2/m^3}{1.4 kg/L} = 3.7 m^2/kg \tag{39}$$

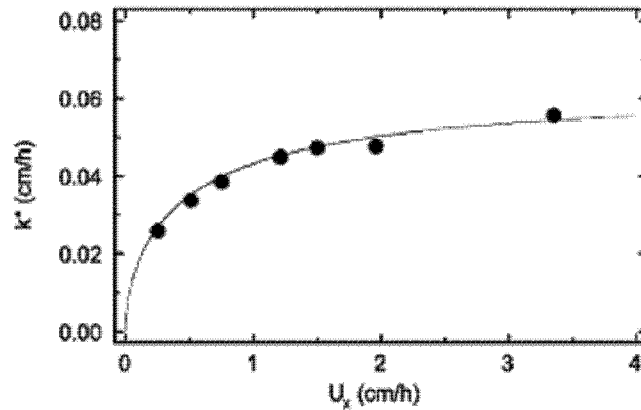The time to remove is then entirely analogous to the solids-free water system shown in (32).

Figure B-4. Solid mass Transfer Coefficient.

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Determine the k_S from (38). The diffusion coefficient for TCE is $D = 9.1 \times 10^{-6}$ cm^2/s.

$$k_S = \frac{2 * 9.1 x 10^{-6} cm^2 / s}{3.7 m^2 / kg * (0.0144 cm)^2} = 2.37 x 10^{-2} kg / m^2 / s$$

Using the $k_L a$ from Perry's[v] (Perry & Green 1984)

$$k_L a = 0.026 \left(\frac{P_g}{V_L} \right)^{0.4} v^{0.5} = 0.026 \left(\frac{.1W}{.001 m^3} \right)^{0.4} \left(2.3 x 10^{-4} m / s \right)^{0.5} = 2.5 x 10^{-3} s^{-1}$$

$$K_{oaL} a_{oa} = \frac{1}{\dfrac{1}{k_D k_S a'} + \dfrac{1}{k_L a}} = \frac{1}{\dfrac{1}{64 L / kg * 2.37 x 10^{-2} kg / m^2 / s * 10^{-3} m^3 / L * 5200 m^2 / m^3} + \dfrac{1}{2.5 x 10^{-3} s^{-1}}} \approx 2.5 x 10^{-3} s^{-1}$$

The above indicates that only the resistance from liquid is needed.

B-4. LABORATORY ANALYSIS

The best method is to find the constants in (31) for solids-free water. Then, $k_L a$ is known for any condition for this water and can be used for scale-up. The solids-water system coefficient (k_S) would then be found from the overall coefficient. These types of tests would provide a fairly high degree of confidence in the scale-up to the actual system being procured since the correlation is not known for k_S.

If only a single test can be done based on vapor space analysis, a fairly crude but useful K_{oa} can be found. Also, it is recommended to use (31) for the scale-up with "a" determined from the single test and assuming the K_{oa} is correlated by (31). Similar to (26):

$$\frac{p}{P} = \frac{K_{oaL} a_{oa} M (X - \dfrac{k_D p}{H})}{K_{oaL} a_{oa} (X - \dfrac{k_D p}{H}) M + \omega_{air}} \tag{40}$$

The mass transfer is normally much smaller than the molar air rate, $\omega << \omega_{air}$ so that:

$$\frac{p}{P} = \frac{K_{oaL} a_{oa} M (X - \dfrac{k_D p}{H})}{\omega_{air}} \tag{41}$$

Solving for X:

$$X = p \left(\frac{\omega_{air}}{P K_{oa} a_{oa} M} + \frac{k_D}{H} \right) = \Gamma p \tag{42}$$

---

v. For the assumed laboratory apparatus.

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Using (34):

$$\frac{dp}{dt} = -K_{oaL}a_{oa}(p - \frac{k_D p}{H\Gamma})$$

(43)

Based on (43), plotting ln(p) versus t will result in a straight line with the following slope:

$$Slope = -K_{oa}a_{oa}\left(1 - \frac{k_D}{H\Gamma}\right)$$

(44)

It may be that $H\Gamma \gg k_D$ so that this last term can be dropped within the experimental error bounds. The stripping depends on Henry's Law constant as shown in (38). If $k_D/H\Gamma \geq 1$, then no stripping occurs and the air flow is increased to obtain stripping.

$$p = p_o e^{-K_{oaL}a_{oa}(1-\frac{k_D}{H\Gamma})t}$$

(45)

If the assumption in (41) cannot be made, a complicated polynomial function results that will require evaluation.

B-5. NOMENCLATURE

a   Bubble specific surface area, m^2/m^3

a'   Particle specific surface area, m^2/m^3

a_{oaL} Overall specific surface area, m^2/m^3

C   Concentration, mol/L

C^* Non-existent liquid concentration in vapor, mol/L

C^{**} Non-existent liquid concentration in solid, mol/L

D   Molecular diffusion, cm^2/s

H   Henry's Law constant, L-atm/mol

H'   Henry's Law constant, mol frac/mol frac

k_D Solid-liquid distribution coefficient, L/kg

k_G Individual gas phase coefficient, m/s

k_L Individual liquid phase coefficient, m/s

$k_L a$ Liquid phase combined coefficient, s^{-1}

k_G' Individual gas phase coefficient, mol/m^2-s

k_L' Individual liquid phase coefficient, mol/m^2-s

K_G Overall coefficient based on gas, m/s

K_L Overall coefficient based on gas, m/s

K_G' Overall coefficient based on gas, mol/m^2-s

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$K_L{}'$	Overall coefficient based on gas, mol/m^2-s
K_{oa}	Overall mass transfer coefficient, m/s
M	Mass solids, kg
p	Partial pressure, atm
P	Pressure, atm
Re_p	Reynolds number, particle
Sc	Schmidt number
Sh	Sherwood number
V_L	Liquid volume in tank, L
X	Solids concentration, mol/kg
X^*	Non-existent solid concentration in liquid, mol/kg
X^{**}	Non-existent solid concentration in gas, mol/kg
α, β, γ	Scaling constants
Γ	Stripping parameter, solids

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Appendix C

Vendor Information

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TIGG MRA
IMPREGNATED VAPOR PHASE
ACTIVATED CARBON

DESCRIPTION

TIGG MRA is a high activity coal based activated carbon which is impregnated with sulfur. The extensive surface area permits optimum distribution of the impregnated reagent, for maximum reaction rate and full stoichiometric utilization. The finished product retains sufficient unimpregnated surface area to function as an effective adsorbent, in addition to its primary chemisorption role, thus allowing reduction of a wide variety of organic contaminants.

TYPICAL PROPERTIES

U.S. Sieve, 90 wt% min	4 x 10*
Apparent Density, (dense packing) g/cc lbs/ft^3	 0.50 – 0.57 32 - 36
Moisture – % max (as packed)	3
CCl$_4$, wt%. min (base carbon)	60
Mercury capacity, wt %	65
Impregnant (sulfur as S$_2$), wt % min, virgin carbon basis	 13

* Also available as 4 mm pellets when a lower pressure drop is required.
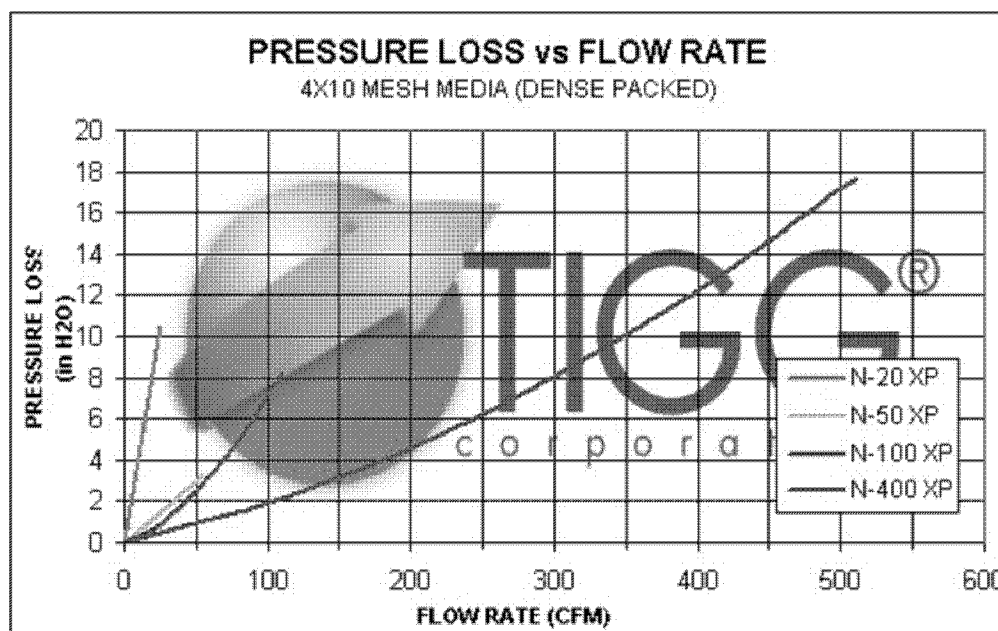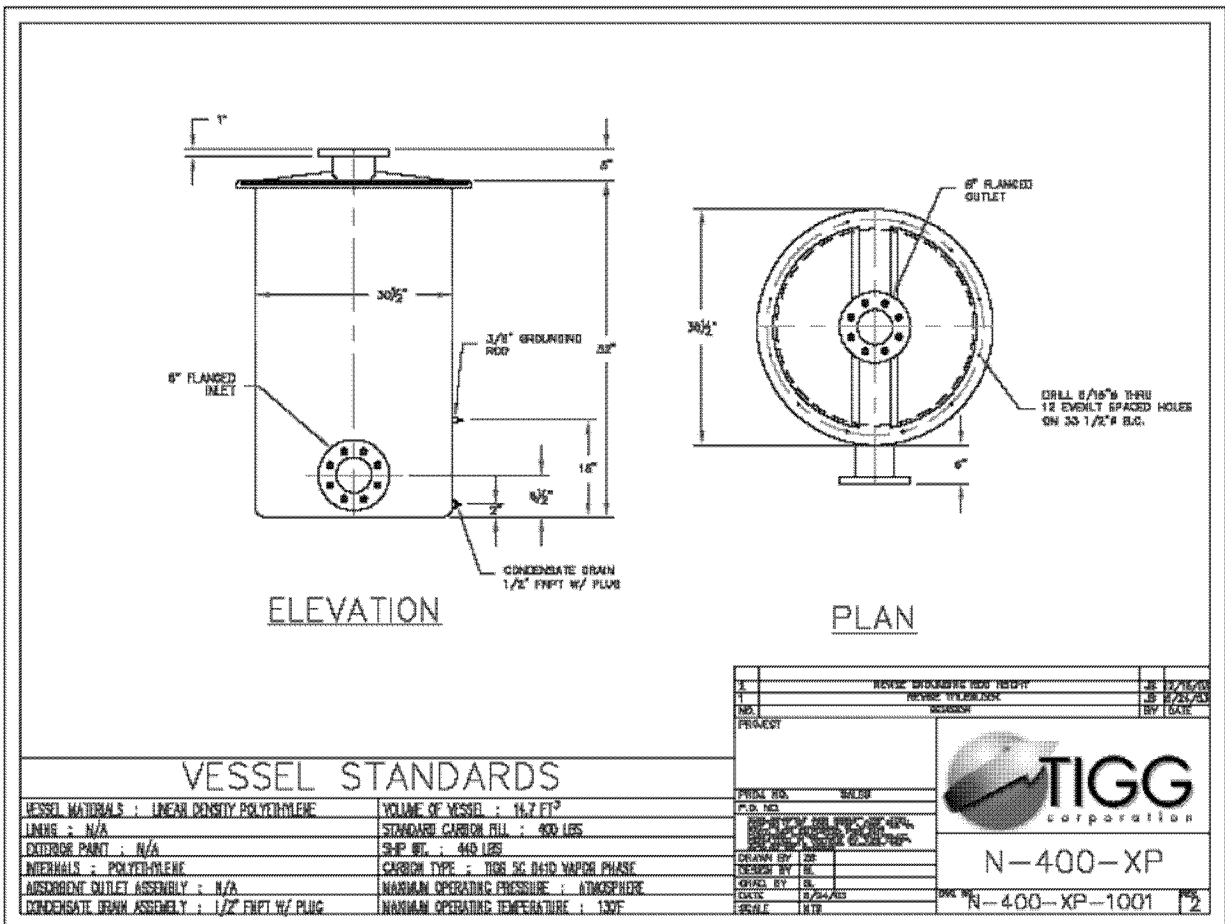
TYPICAL APPLICATIONS

TIGG MRA is recommended for applications where mercury is to be removed from natural gas, air, hydrogen or other gas streams. TIGG MRA performs well in high humidity streams and at elevated temperatures.

Standard packaging is in 1000 lb supersaks. Metal drums, fiber drums and 50 lb bags, are available for a premium.

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ELEVATION   PLAN

VESSEL STANDARDS

VESSEL MATERIALS : LINEAR DENSITY POLYETHYLENE	VOLUME OF VESSEL : 16.7 FT³
LINING : N/A	STANDARD CARBON FILL : 400 LBS
EXTERIOR PAINT : N/A	SHIP WT. : 440 LBS
INTERNALS : POLYETHYLENE	CARBON TYPE : TIGG 5C 841D VAPOR PHASE
ABSORBENT OUTLET ASSEMBLY : N/A	MAXIMUM OPERATING PRESSURE : ATMOSPHERE
CONDENSATE DRAIN ASSEMBLY : 1/2" FNPT W/ PLUG	MAXIMUM OPERATING TEMPERATURE : 130F

TIGG corporation

N-400-XP

N-400-XP-1001

PRESSURE LOSS vs FLOW RATE
4X10 MESH MEDIA (DENSE PACKED)

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NF RPS
RADIATION PROTECTION SYSTEMS
888.637.7779
60 Leonard Drive
Groton, CT 06340
www.nfsrps.com

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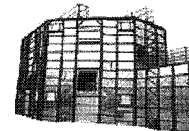- Brochures/Manuals/Data

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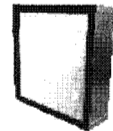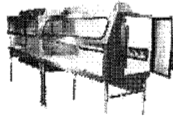
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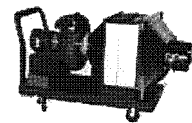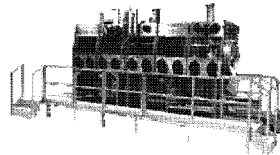
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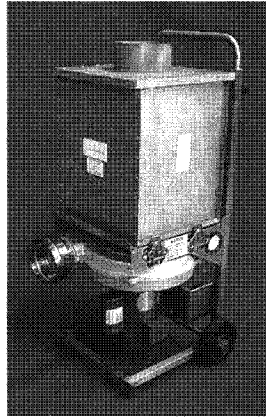
FM34- 500 CFM HEPA FILTRATION UNIT (SP-505A)

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Code: **FM34**

Shipping weight: **180** pounds

FM34 500 CFM HEPA filtration unit 99.97% efficiency @ 0.3 micron

The SP-505A HEPA filtration unit has the highest flowrate and static pressure rating available for a unit of its size and weight. Delivering over 515 CFM flow at 1" of static pressure, the SP-505A outperforms anything in it's category and sets the standard for high quality air cleaning equipment in a small, highly mobile package. the handtruck configuration allows operation in either a horizontal or vertical position and facilitates moving and locating the unit close to the work site thereby eliminating the necessity for long lengths of flex duct.

A high flow portable, filter/blower unit providing high efficiency particulate air filtration with the following attributes:

1. Integral stainless steel frame, blower mount and filter retainer assembly capable of operating in either a horizontal or vertical position.
2. Motor, 3/4 horsepower 3450 rpm, 115 vac, single phase, 9.6 amp.
3. Blower, direct drive, non-overloading, with back curved blades and aluminum housing and wheel. Rated at 515 CFM at 1" sp.g. and 210 at 6" sp.g.
4. Manual starter switch with thermal overload mounted in a NEMA 1 enclosure and equipped with 15' service cord.
5. HEPA filter, metal framed, 14" x 14" x 17" long with integral inlet plenum and inlet connector for 6" Dia. flex duct. Filter rated at 300 CFM @ 1" sp.wg. and 99.97 efficient for 0.3 micron particles. DOP test at 100% and 20% of rated flow.
6. Prefilter, 2" thick x 12.5" x 12.5" multi-density polyester.
7. Magnehelic gauge, 0-10" water gauge, minihelic type.
8. Dimensions: 38" long x 19" high x 19" wide.
9. Weight: approx. 80 lbs.

Options:

- Slide gate flow control on blower discharge, P/N AM-08
- Loss of flow alarm, P/N GT07
- Custom inlet/outlet sizes available, call for details

Spare parts:

- HEPA filter AK-36
- Prefilter AK-37
- Minihelic gauge AR-13
- Motor/blower AL-19
- Starter switch AV-31
- Wheel HB-08
- Inlet adapter, 6" to 8" CR-04

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FORCED AIR HEATING PRODUCTS
NON-HEAT PUMP/SPIN FINNED ELEMENTS
PRICE SHEET - LIST ©

EFFECTIVE
APRIL 1, 2004

ELECTRIC PLENUM HEATER
ELECTRO-MATE™ - PATENTED & REGISTERED
THE OLDEST & ONLY U.S. MANUFACTURED TRUE PLENUM HEATER

Primary application, gas/oil furnace with electric Dual Heat/Load Management, A/C optional

Upflow - 18"	Upflow - 15"				
EM-LV25-KIT	N/A	$275	5kW add-on kit to EM-LV20218	5	kW
EM-LV20218	EM-LV20215	960	2 Stg, 10kW each	20	kW
EM-LV15278	EM-LV15275	895	2 Stg, 7.5kW each	15	kW
EM-LV10118	EM-LV10115	730	1 Stg, 10kW	10	kW
Downflow - 18"	**Downflow - 15"**				
EM-LD20218	EM-LD20215	$1040	2 Stg, 10kW each	20	kW
EM-LD15278	EM-LD15275	975	2 Stg, 7.5kW each	15	kW
EM-LD10118	EM-LD10115	760	1 Stg, 10kW	10	kW

CUSTOM DUCT HEATERS WITH DFC OPTION

Typical application, non-plenum combining kW in different trunk lines

IH-31	380	Controller, any combination up to 3 heaters. Also applies to EM-WC and EM-DI.		
EM-II10118	$355	18"w x 3"h, lays flat for airflow - element 18"d	10	kW
EM-II10114	355	11"h x 4.5"w, multi-directional - element 18"d	10	kW

Other kW sizes and shapes available.

WARMFLO™ CONTROLLED
ELECTRIC PLENUM HEATER

DUAL HEAT/AIR CONDITIONING APPLICATION

WarmFlo II electric conversion package - applies to gas/oil/wood temperature sensor controlled

Upflow - 18"	Upflow - 15"				
EM-WU30-KIT	N/A	$ 265	WarmFlo 5kW add-on kit to 25kW	5	kW
EM-WU25458	N/A	1220	WarmFlo staging	25	kW
EM-WU20458	EM-WU20455	1030	WarmFlo staging	20	kW
EM-WU15358	EM-WU15355	930	WarmFlo staging	15	kW
EM-WU10258	EM-WU10255	820	WarmFlo staging	10	kW
Downflow - 18"	**Downflow - 15"**				
EM-WD20458	EM-WD20455	$1060	WarmFlo staging	20	kW
EM-WD15358	EM-WD15355	960	WarmFlo staging	15	kW
EM-WD10258	EM-WD10255	850	WarmFlo staging	10	kW

Product application code needed for WarmFlo II heater (part #UIC9266) - please specify: "EMA"   Dial-in air outlet temperature
"EMW"   OT sensing, WarmFlo curve

Controller Interface
WF-EM3	$138	WarmFlo controller - non-HP, for WarmFlo models

WARMFLO II/ELECTRO-MATE (Spin finned elements) - Three Phase, 208V

Upflow - 18"	Upflow - 15"				
EM-WU22478	N/A	$1389	WarmFlo/Electro-Mate 208V 3-phase	22	kW
EM-WU14358	N/A	1169	WarmFlo/Electro-Mate 208V 3-phase	14.4	kW

ELECTRO INDUSTRIES, INC.
2150 West River Street, PO Box 538, Monticello, MN 55362
763.295.4138 • 800.922.4138 • fax 763.295.4434
sales@electromn.com • www.electromn.com

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DUCT HEATERS

Electro-Duct - Basic Electric Element Package

Typical application is ground source heat pump or above any air handler, top blower

EM-DI2035H	$480	Insert 8"w x 10"d, 2 Stg @ 4.8kW, 1 Stg @ 9.6kW	19.2	kW
EM-DI1535H	395	Insert 8"w x 10"d, 3 Stg @ 4.8kW	14.4	kW
EM-DI1025H	285	Insert 8"w x 10"d, 2 Stg @ 4.8kW	9.6	kW
EM-DI2035L	535	Insert 8"w x 16"d, 2 Stg @ 4.8kW, 1 Stg @ 9.6kW	19.2	kW
EM-DI1535L	415	Insert 8"w x 16"d, 3 Stg @ 4.8kW	14.4	kW
EM-DI1025L	295	Insert 8"w x 16"d, 2 Stg @ 4.8kW	9.6	kW
EM-DI2035C	555	Plenum 16"w x 16"d, 2 Stg @ 4.8kW, 1 Stg @ 9.6kW	19.2	kW
EM-DI1535C	470	Plenum 16"w x 16"d, 3 Stg @ 4.8kW	14.4	kW
EM-DI1025C	350	Plenum 16"w x 16"d, 2 Stg @ 4.8kW	9.6	kW

MAKE-UP AIR/HEAT EXCHANGER/BOOST HEATERS

Single Sensor - Controls Duct Temperature - Element Modulation

Typical application is required - heat pump, ERV/HRV defrost, cold air, etc.

EM-WX0111R	$310	Complete 6" pipe section, 120V, 150 CFM	1	kW
EM-WX0212R	345	Complete 8" pipe section, 240V, 250 CFM	2.5	kW
EM-WX0515R	370	Complete 8" pipe section, 240V, 350 CFM	5	kW
EM-WX1025R	440	Complete 10" pipe section, 240V, 700 CFM	10	kW
EM-WC0313H	310	Insert 8"w x 10"d element, 240V	2.9	kW
EM-WC0515H	350	Insert 8"w x 10"d element, 240V	4.8	kW
EM-WC0515L	360	Insert 8"w x 16"d element, 240V	4.8	kW
EM-WC1025H	400	Insert 8"w x 10"d element, 240V	9.6	kW
EM-WC1025L	415	Insert 8"w x 16"d element, 240V	9.6	kW
EM-WM1535L	590	Insert 8"w x 16"d element, 240V, single phase	14.4	kW
EM-WM2035L	675	Insert 8"w x 16"d element, 240V, single phase	19.2	kW
EM-WM1134H	535	Insert 8"w x 10"d element, 208V, three phase	10	kW
EM-WM1536L	685	Insert 8"w x 16"d element, 208V, three phase	15	kW

Outlet temperature default code D, 12° steps, 40° to 124°. If smaller range is desired, specify other temperature codes. Document HD308 has details.

ACCESSORIES

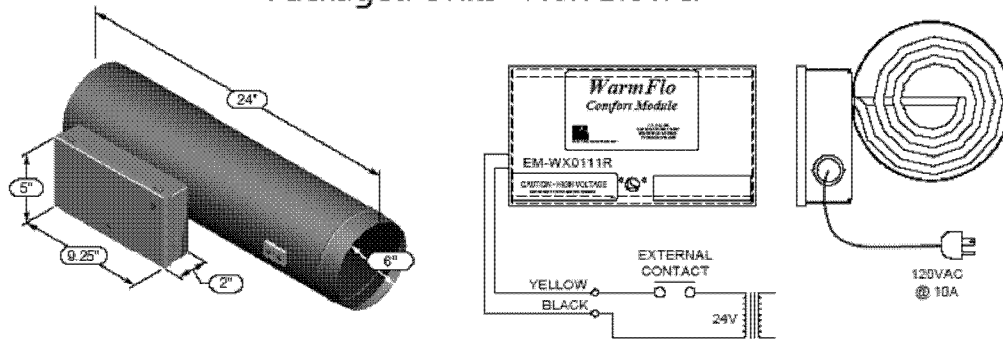|		
HP5739	$315	Conversion of Electro-Mate (DFC type) to interface with heat pump, electric heat, and gas furnace
SOT-EM-60	95	Stat override timer, switches to standby in 20-60 minutes
EM-5716	65	Single feed for 2 CB - 2 stg GE breakers
EM-5717	70	Single feed for 3 CB - 3 stg GE breakers
EM5713	48	Limit probe low 100°, 4"
EM-5750	48	Deflector Kit A 18"-20.5" V
EM-5751	50	Deflector Kit B 21"-22.5" V

## REPLACEMENT PARTS LIST

Request document XL005

Notes:
1. This sheet represents only a sampling of basic models. Call for pricing on other sizes, types, or configurations.
2. Base and quantity discounts can apply, check your assigned discount.
3. Price and specification subject to change without notice.
4. F.O.B. Monticello, MN dock, depending upon quantity, other freight and shipping arrangements can be made.
5. All products have a two-year parts warranty from date of original installation.

EL050

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Packaged Units - Non-Blower

EM-WX0111R - 1,000-watt, 120V plug-in
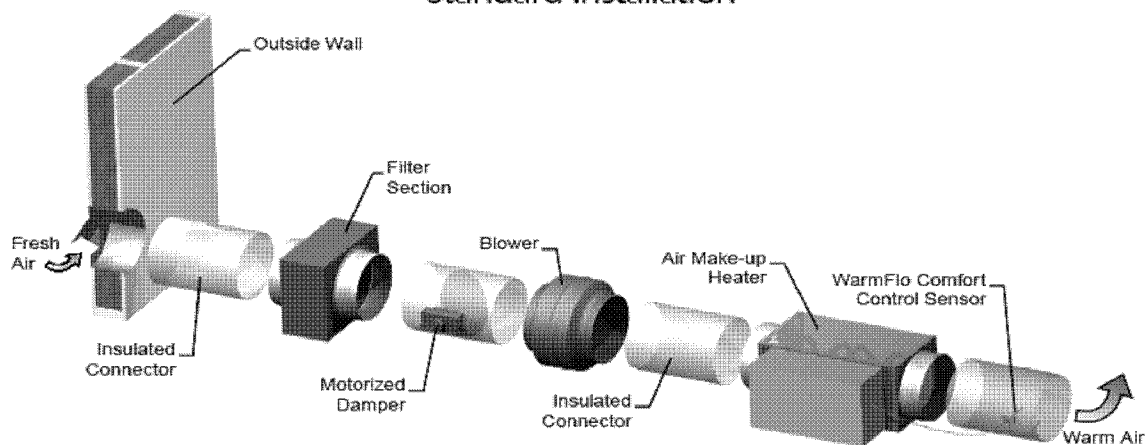150 CFM rating, 6" round duct section
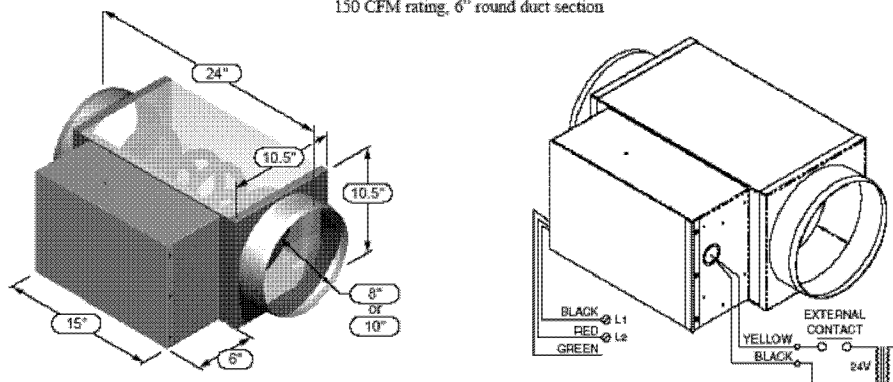
EM-WX0212R - 2,500-watt, 240V
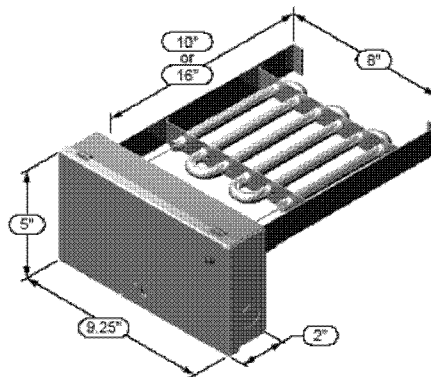250 CFM rating, 8" round duct section

EM-WX0515R - 5,000-watt, 240V
350 CFM rating, 8" round duct section

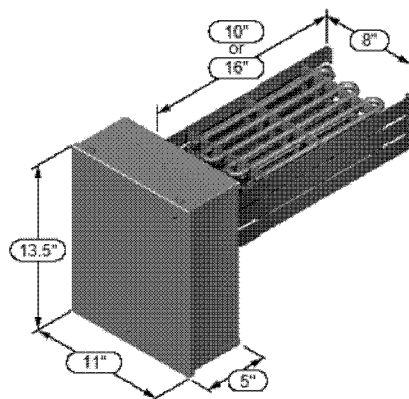EM-WX1025R - 10,000-watt, 240V
700 CFM rating, 10" round duct section
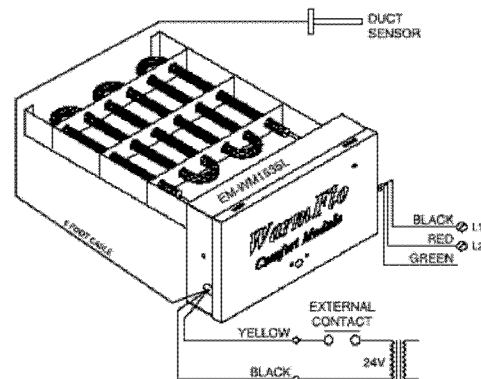
Standard Installation

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Insert Element Rack

EM-WC0313H - 2,880-watt, 240V
300 CFM rating, 8" x 10"d element rack

EM-WC0515H - 4,800-watt, 240V
400 CFM rating, 8" x 10"d element rack

EM-WC0515L - 4,800-watt, 240V
400 CFM rating, 8" x 16"d element rack

EM-WC1025L - 9,600-watt, 240V
800 CFM rating, 8" x 16"d element rack

EM-WM1535L - 15,000-watt, 240V
1,100 CFM rating, 8" x 16"d element rack

EM-WM2035L - 20,000-watt, 240V
1,300 CFM rating, 8" x 16"d element rack
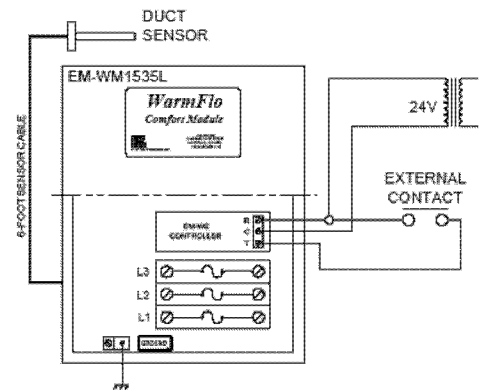
EM-WM1134H - 10,800-watt, 208V 3-phase
800 CFM rating, 8" x 10"d element rack

EM-WM1536L - 15,000-watt, 208V 3-phase
1,100 CFM rating, 8" x 16"d element rack

Electrical Source Power:

- See nameplate for voltage rating, amp draw, and maximum watts
- 120V single-phase, 240V single-phase, or 208V three-phase - depending upon model and size
- 120V model has 8' plug-in cord
- All other models, terminal block connections (copper wire only)
- Units above 10 kW include internal fusing

24-volt control:

- External 24-volt source is required for operation
- Turn-on (on/off function) accomplished with the presence of 24-volt source
- System or external contact closure provides 24 volts to this unit
  - Pressure differential switch
  - Inlet damper end switch
  - Relay connected to blower motor, contact closure
  - Exhaust motor current switch contact
  - Thermostat, blower function "G" (parallel connection)
  - Temperature sensing thermostat (must also operate blower)

Packaged Units - Self-Contained, Blower
Contact Factory - Request Document #0155

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CFM Chart

Temperature Rise Needed		80	70	60	50	40	30
Model Number	Watts*	CFM	CFM	CFM	CFM	CFM	CFM
EM-WX0111R	1000	40	45	53	63	79	105
EM-WX0515R	5000	197	225	262	319	393	525
EM-WX1025R	10000	393	450	525	630	787	1050
EM-WH0515J	5000	175	222	260	316	388	520
EM-WH1025K	10000	365	420	490	590	718	980
EM-WC0313H	2880	114	130	152	182	228	303
EM-WC0515H	4800	189	216	252	302	378	504
EM-WC0515L	4800	189	216	252	302	378	504
EM-WC1025L	9600	378	432	504	604	756	1007
EM-WM1535L	14400	567	648	756	907	1133	1511
EM-WM2035L	19200	756	863	1007	1209	1511	2015
EM-WM1134H	10800	425	486	567	680	850	1133
EM-WM1536L	15000	593	677	790	948	1185	1580

*At maximum capacity, duct sensor reduces watts as required.

Efficient - 100%, Plus Duct Sensor Modulates Elements

HOW TO ORDER

Select model number **AND** state temperature selection code.

Warm Air Temperature Selection

The unit includes an 8-position dial switch to set the desired outlet sensor temperature. In order to give this 8-position dial switch proper definition and accuracy, when ordering select the temperature **range** which meets your application.

	Min.		Max.
"Code E"	68	to	96
"Code H"	88	to	102
"Code C"	30	to	72
"Code B"	96	to	124

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